WBS 6.6
Muons

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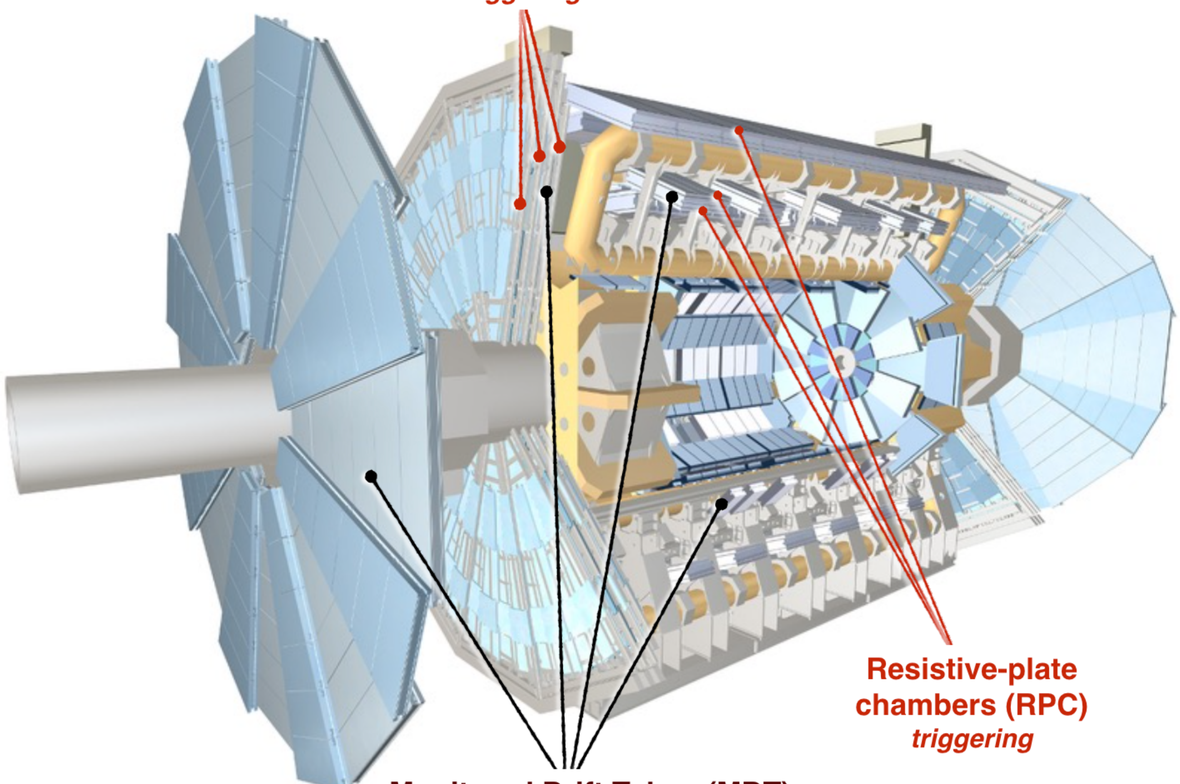
U.S. ATLAS HL-LHC Upgrade Director's Review
Brookhaven National Laboratory
Upton, New York
January 20-22, 2016

ATLAS Muon Spectrometer

Upgrades to the muon spectrometer are required to handle increased rates and fakes associated with HL-LHC luminosities and the new ATLAS wide L0/L1 trigger system



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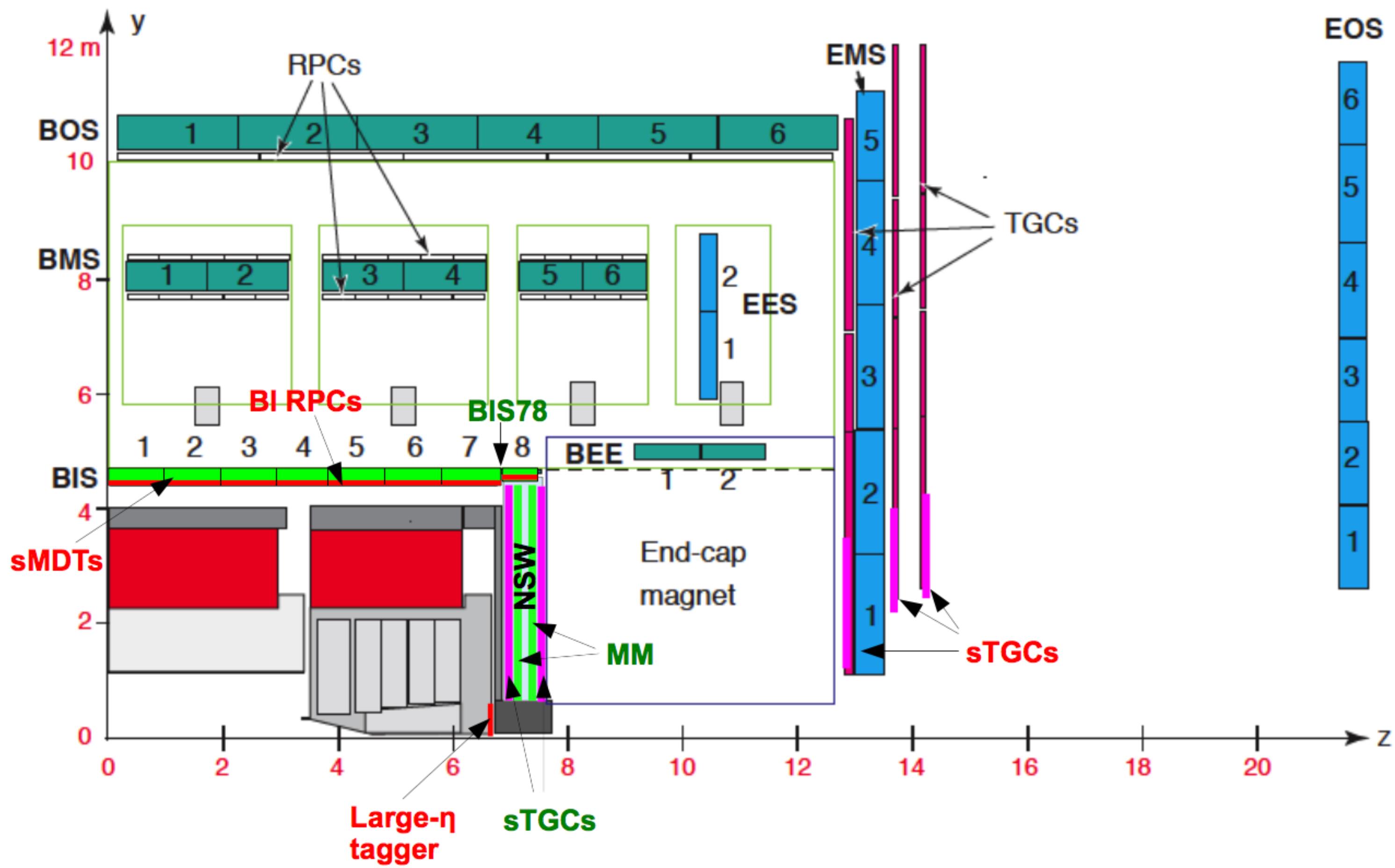

Physics Motivation

Triggering and recording High-p$_T$ leptons (muons) are critical to nearly every physics objective of the ATLAS experiment

Detector system	Trigger–DAQ		Inner Tracker	Inner Tracker + Muon Spectrometer	Inner Tracker + Calorimeter		
Object Performance / Physics Process	Efficiency/ Thresholds $\mu^\pm$	$e^\pm$	b-tagging	$\mu^\pm$ Identification/ Resolution	Pile-up rejection	Jets	E_T^{miss}
$H \longrightarrow 4\mu$	✓			✓			
VBF $H \to ZZ^{(*)} \to \ell\ell\ell\ell$	✓	✓		✓	✓	✓	
VBF $H \to WW^{(*)} \to \ell\nu\ell\nu$	✓	✓	✓	✓	✓	✓	✓
SM VBS ssWW	✓	✓		✓	✓	✓	✓
SUSY, $\chi_1^\pm \chi_2^o \to \ell b\bar{b} + X$	✓	✓	✓	✓	✓	✓	✓
BSM $HH \to b\bar{b}b\bar{b}$			✓			✓	

ATLAS HL-LHC Upgrade

Muon Spectrometer	Scoping Scenarios Reference (275 MCHF)	Middle (235 MCHF)	Low (200 MCHF)
Barrel Detectors and Electronics			
RPC Trigger Electronics	✓	✓	✓
MDT Front-End and readout electronics (BI+BM+BO)	✓	✓ [BM+BO only]	✓ [BM+BO only]
RPC Inner layer in the whole layer	✓	✓ [in half layer only]	✗
Barrel Inner sMDT Detectors in the whole layer	✓	✓ [in half layer only]	✗
MDT L0 Trigger Electronics (BI +BM+BO)	✓	✓ [BI +BM only]	✓ [BI +BM only]
End-cap and Forward Muon Detectors and Electronics			
TGC Trigger Electronics	✓	✓	✓
MDT L0 Trigger and Front-End read-out electronics (EE+EM+EO)	✓	✓ [EE +EM only]	✓ [EE +EM only]
sTGC Detectors in Big Wheel Inner Ring	✓	✓	✓
Very-forward Muon tagger	✓	✗	✗

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Barrel (RPC) and end-cap (TGC) triggering electronics must be replaced to cope with hit rates at the HL-LHC.

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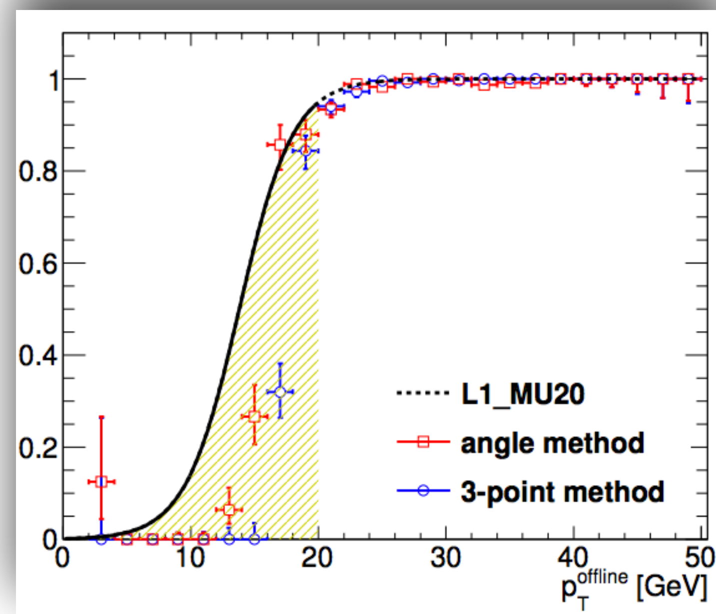

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Very-forward Muon tagger	✓	✗	✗

Gas gain on currently installed RPC's must be lowered to meet lifetime limitations (0.3 C/cm²).

To maintain trigger efficiency, RPC's will be installed at the inner layer. To make room for RPC's at BIS, sMDT's will replace MDT's.

Trigger	L0 Trigger Efficiency
old RPCs	0.65
+BI RPCs (stations 4-6)	0.82
+BI RPCs (fulll)	0.94

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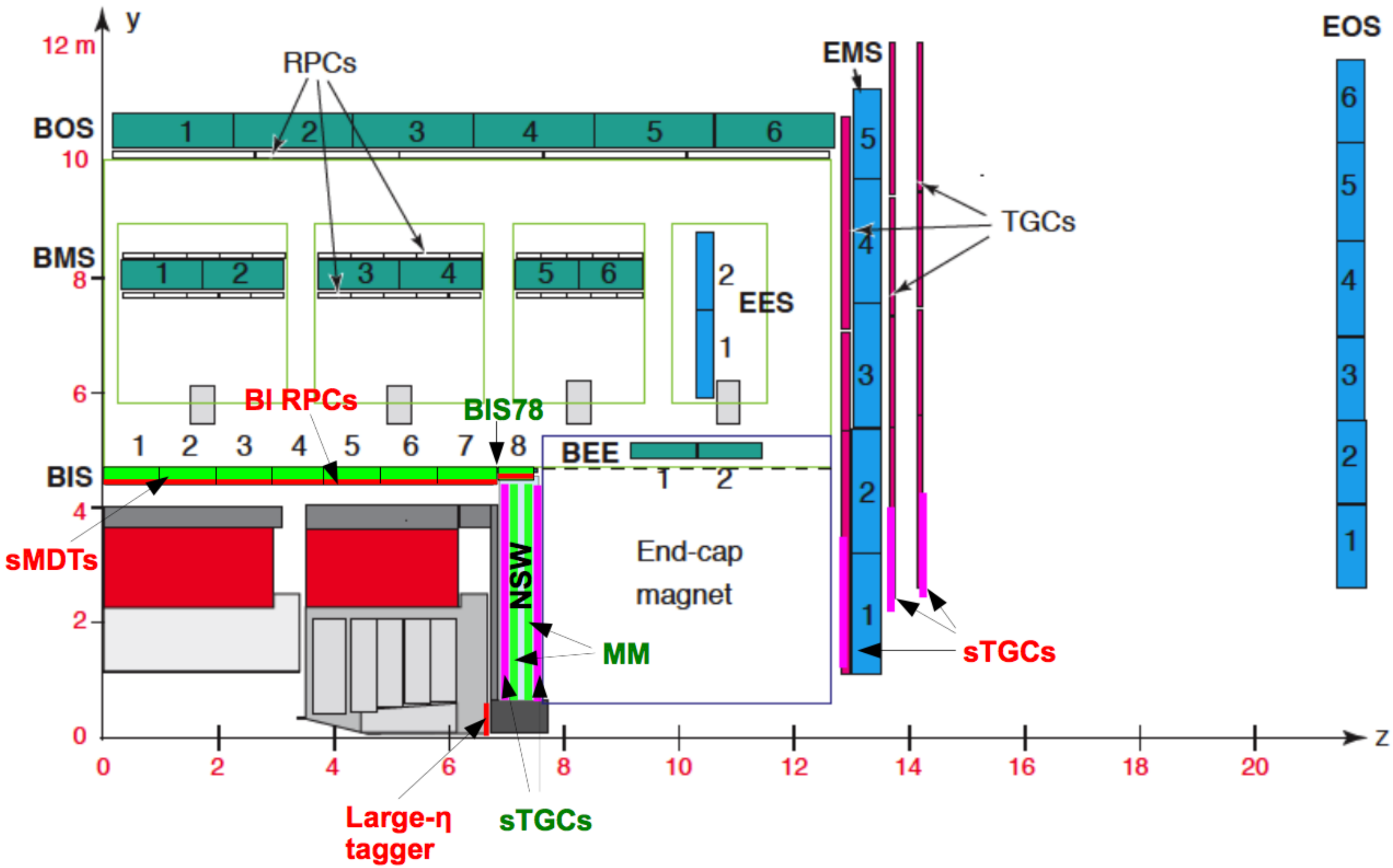

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Add a very-forward muon tagger (between end-cap calorimeter and JD) to allow tagging of inner detector tracks as muons ➜ $2.7 < \eta < 4.0$

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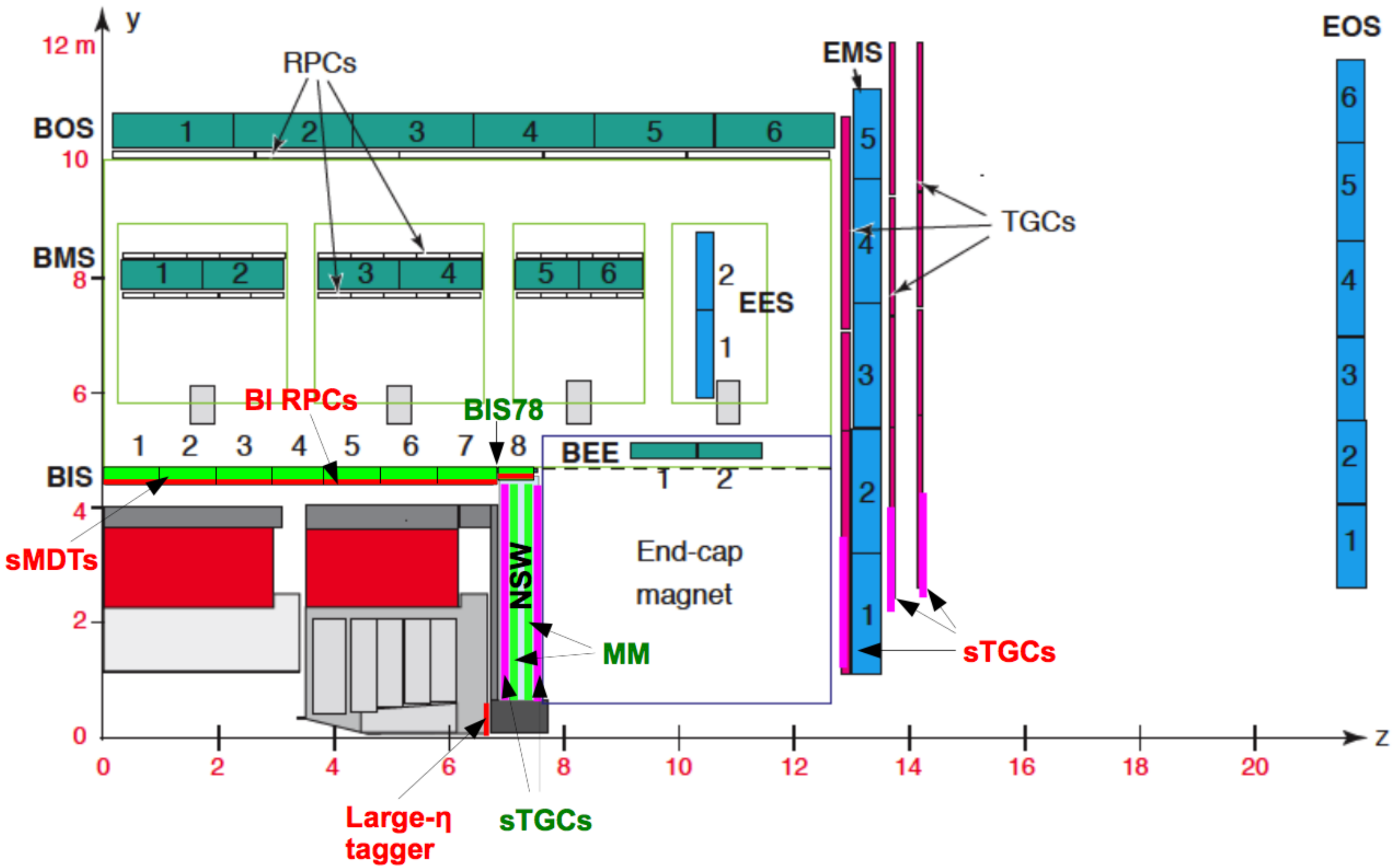

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Barrel (RPC) and end-cap (TGC) triggering electronics must be replaced to cope with hit rates at the HL-LHC.

MDT readout electronics must be replaced to cope with hit rates at the HL-LHC.

To reduce fakes, MDT information will be integrated the into L0/L1 trigger to sharpen p_T selectivity of tracks.

Gas gain on currently installed RPC's must be

USATLAS scope is to lead the design and construction of the trigger and readout electronics for the MDT system

- **Leverages US expertise (MDT, NSW)**
- **High impact contribution**
- **Reasonable costs and low risk**

η spatial resolution.

Add a very-forward muon tagger (between end-cap calorimeter and JD) to allow tagging of inner detector tracks as muons ➔ 2.7< η < 4.0

ATLAS Muon Core Costs

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Very-forward Muon tagger	✓	✗	✗

WBS	Item	Reference Total Cost [kCHF]
5	**Muon system**	**34,084**
5.1	**MDT**	**7,692**
5.1.1	sMDT detector	2,022
5.1.2	sMDT installation basket	20
5.1.3	Mezzanine cards	4,000
5.1.4	CSM cards	1,650
5.2	**RPC**	**7,989**
5.2.1	Detectors	3,034
5.2.2	Installation mock-up	50
5.2.3	Installation tooling	100
5.2.4	On-detector electronics (DCT)	4,805
5.3	**TGC**	**4,436**
5.3.1	On-detector electronics (PS)	2,136
5.3.2	sTGC on BW inner ring	2,300
5.4	**High η-tagger**	**3,500**
5.4.1	Detector	1,100
5.4.2	FE electronics	1,500
5.4.3	Services+infrastructure	900
5.5	**Power System**	**10,467**
5.5.1	MDT	2,770
5.5.2	RPC	4,227
5.5.3	TGC	3,470

Proposed US Scope

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Proposed U.S. Scope (WBS)

Item	Description
6.6	Muon
6.6.1.1	**PCB for Mezzanine - Arizona**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.2	**TDC - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.3	**CSM - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.5	**sMDT - Michigan**
	Chamber Construction
6.6.3.5	**sMDT - MSU**
	Tube Construction
6.6.4.4	**HEB - Illinois**
	Design/Prototype
	Pre-Production
	Production & Testing

L4 Deliverables

1. PCB for Mezzanine
2. TDC (Time to Digital Converter)
3. CSM (Chamber Service Module)
4. HEB (Hit Extraction Board)
5. sMDT (small Monitored Drift Tubes)

ATLAS MDT Detectors

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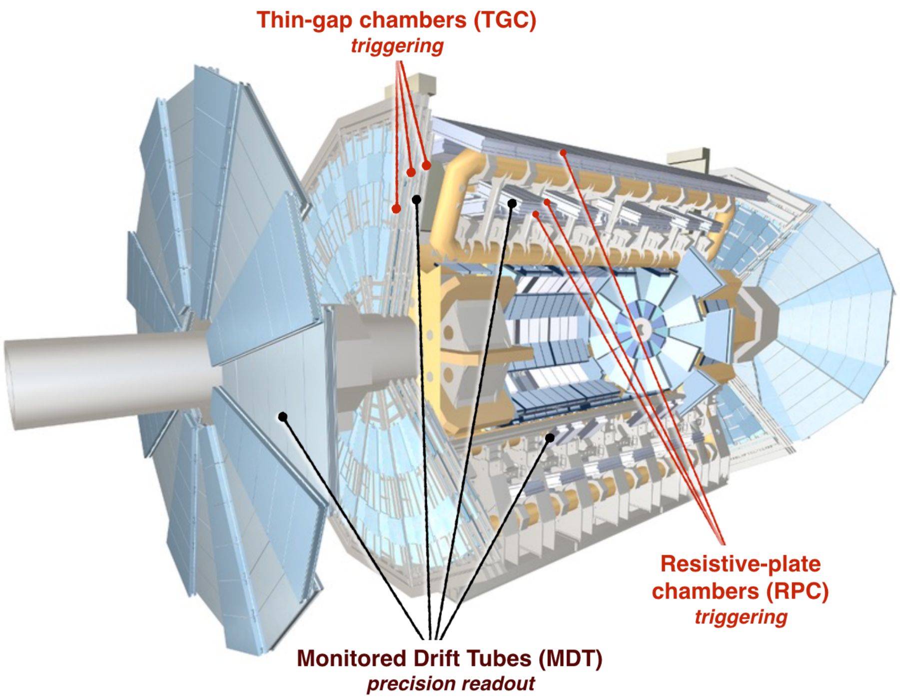
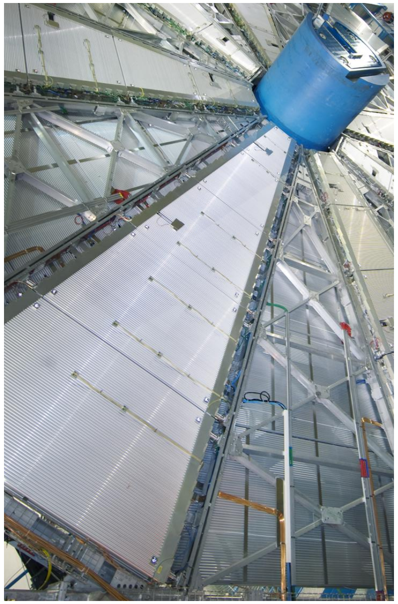
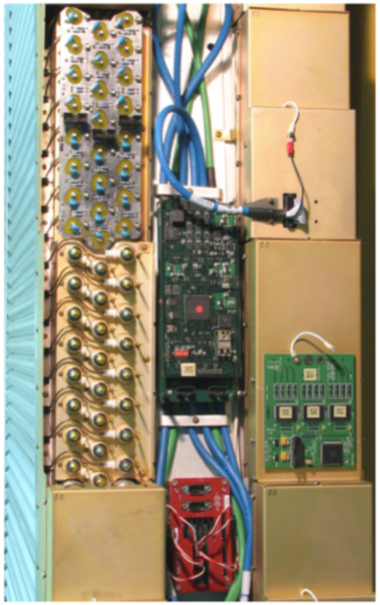
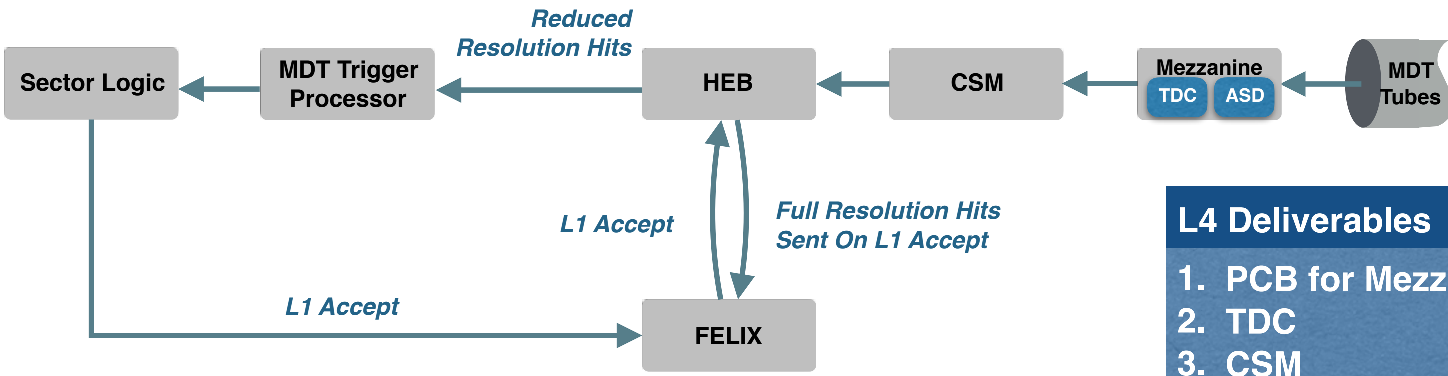






HL-LHC MDT Readout System



L4 Deliverables

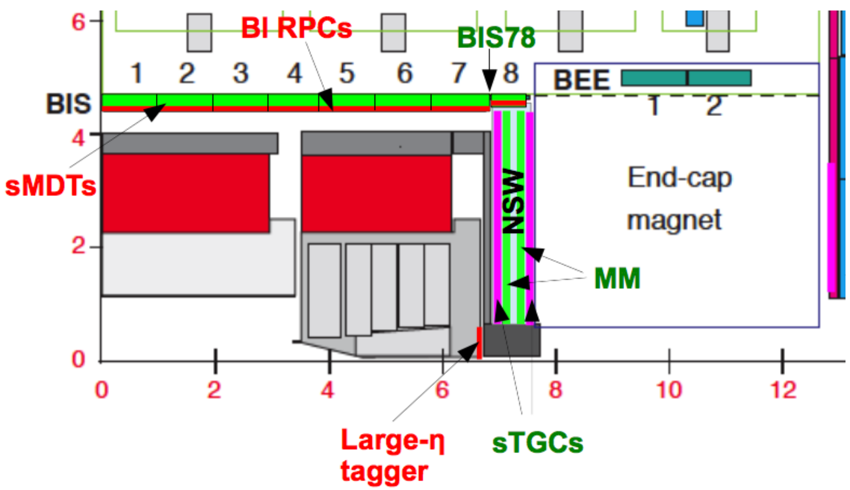
1. PCB for Mezzanine
2. TDC
3. CSM
4. HEB
5. sMDT

- Raw drift signals for up to 24 MDT tubes are amplified, shaped and digitized by ASD chips, then routed to the TDC which stores arrival times of leading and trailing edges of the signal.
- At the CSM, data are formatted, stored, and sent via optical link to the Hit Extraction Board (HEB).
- The HEB sends reduced resolution hits to the trigger processor which performs segment finding and track fitting.
- On Level 1 accept by sector logic, the HEB sends full resolution hits to FELIX for readout.

This entirely NSF-funded construction project would lead development of the front-end system, <u>including sMDT detectors</u> which will replace inner barrel MDT's!

sMDT Detectors

- Replacing current MDT's with sMDT's to maintain trigger efficiency and precision tracking - especially after RPC gain is lowered
- Construction 50% Umich and 50% MPI
- Utilize existing infrastructure at UMich and tooling already developed at MPI (big cost savings)
- ATLAS management strongly encourages UMich/MPI arrangement to solve sMDT issue



Deliverables		
Deliverable	**US Interests**	**International Interests**
sMDT *design & construction*	**UMich (50%)**	**MPI (50%)**

CORE Costs from Scoping Doc

WBS	Item	Reference Total Cost [kCHF]
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Mezzanine Card

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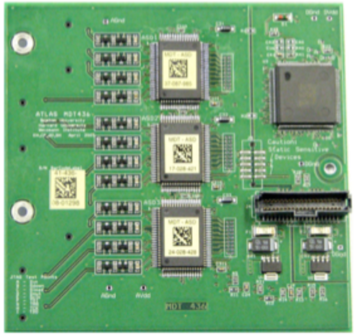

- Arizona will lead the development of the PCB board for the TDC and ASD components

- Arizona developed PCB board used for front-end chips (VMM) for the ATLAS Phase I NSW, which was far more challenging.

Deliverables

Deliverable	US Interests	International Interests
PCB *design & construction*	**Arizona**	-

Costs from Scoping Doc

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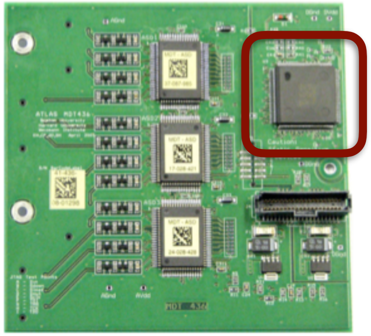
TDC

- <u>Functionality:</u> TDC produces arrival times of leading & trailing edges of tube signals, as well as an identifier word for the corresponding tube, and sends to the CSM

- UMich in collaboration with MPI to develop ASIC-based TDC

- Japan developing an FPGA-based TDC

- Umich very experienced in developing ASIC's - developed trigger data serializer (ASIC) used for sTGC readout in NSW



Deliverables

Deliverable	US Interests	International Interests
TDC *design & construction*	**UMich**	**Japan, MPI**

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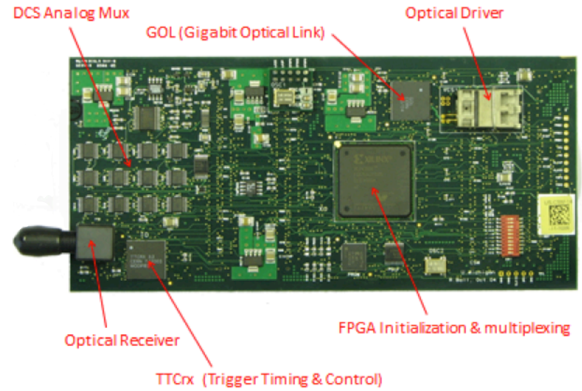
CSM

- <u>Functionality:</u>
  - One MDT chamber, up to 18 mezzanines, are controlled by a local processor board (CSM)
  - The CSM broadcasts the TTC signals to the TDCs, and collects data from the TDCs
  - At the CSM, data are formatted, stored, and sent via optical link to the Hit Extraction Board (HEB)
- UMich developed previous CSM for MDT readout and developing FPGA-based router board for Phase I NSW
- CSM R&D currently driving entire front-end system design



Deliverables

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CSM *design & construction*	UMich	-

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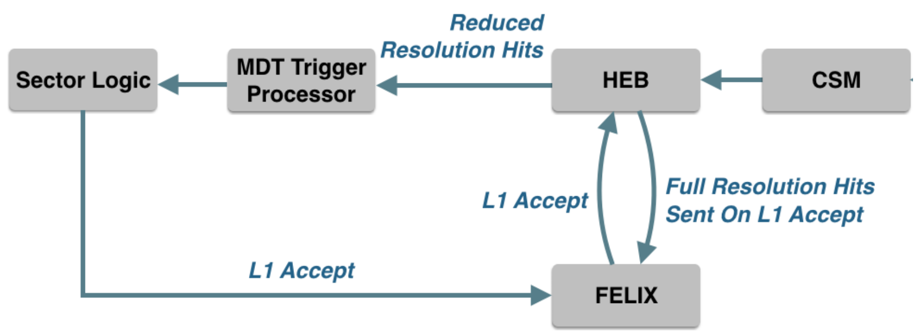
HEB

- <u>Functionality:</u>
  - Receive data from front-end boards.
  - Provide data buffering for L0/L1.
  - Deliver low-latency, low-granularity signals to hardware trigger.
  - Interface with network-based trigger/DAQ system (FELIX).
- Electronics shop/engineers at Illinois experienced with FPGA programming



Deliverables

Deliverable	US Interests	International Interests
HEB *design & construction*	Illinois	MPI, Japan

CORE Costs from Scoping Doc

WBS	Item	Reference Total Cost [kCHF]
5	**Muon system**	**34,084**
5.1	**MDT**	**7,692**
5.1.1	sMDT detector	2,022
5.1.2	sMDT installation basket	20
5.1.3	Mezzanine cards	4,000
5.1.4	CSM cards	1,650

Status of R&D

- Simulation in place to study the performance of potential MDT electronics system designs
    - US developed design currently shown to be able to read off all hits from the MDT with a hit rate of ~300 kHz/tube and < 1.5 μs latency
- Simulation has been cross-checked in hardware with current mezzanine cards connected to a CSM at current hit rates
- Existing cables, which are very difficult to replace in the detector, can send data at 320 Mbps on two differential pairs (currently run at 80 Mbps on one pair)
- US ramping up on all other efforts. Leading the development of demonstrator electronics for the IDR/TDR (TDC, CSM, and HEB)

More on R&D in Anyes' (L2 R&D Manager) talk during Muon breakout

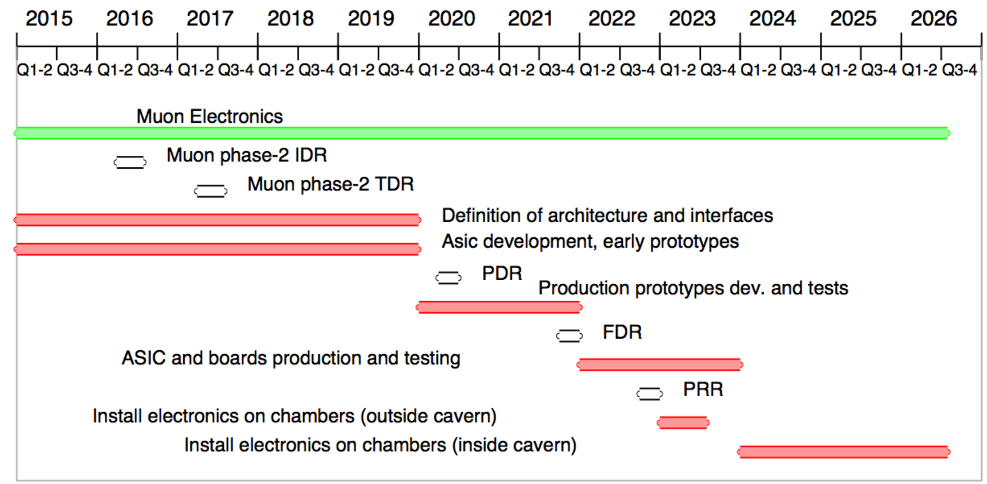
Research & Development

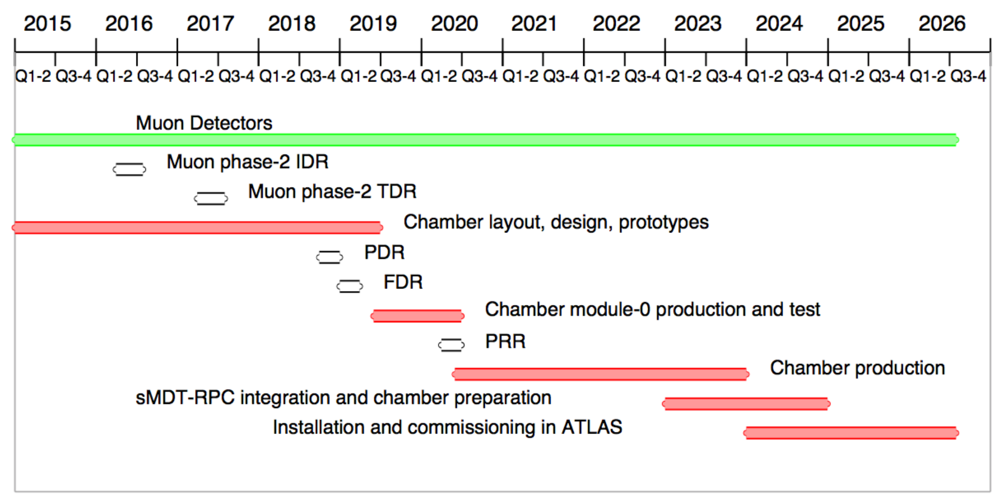
- Each deliverable has developed an R&D plan to be prepared for construction
- sMDT's (UMich, MSU) do not require R&D per se - however tooling needs to be developed and tube construction begins before FY20 to allow for float in the existing ATLAS schedule
- PCB for Mezzanine (Arizona), TDC (UMich), and CSM (UMich) will be developing more advanced prototypes during R&D, as the construction timeline is slightly earlier due to the need to install electronics on-chamber for the sMDT's
- The HEB (Illinois) is off-detector electronics and therefore has a later timeline. Early R&D is more related to the design of trigger processing for the MDT's.
- Ops program scrub the R&D budget on a yearly basis. R&D for each deliverable is adapted to what needs to be accomplished within the available budget.

Item	Description	AY k$	FY17	FY18	FY19	FY20	Total (k$)
6.6	Muon	Total	222.32	681.24	1,296.64	505.95	2,706.14
		Labor	212.32	486.24	1,069.64	417.95	2,186.14
		Material	10.00	180.00	215.00	88.00	493.00
		Travel	-	15.00	12.00	-	27.00
		FTEs	1.65	4.44	10.06	3.97	20.12

Schedule

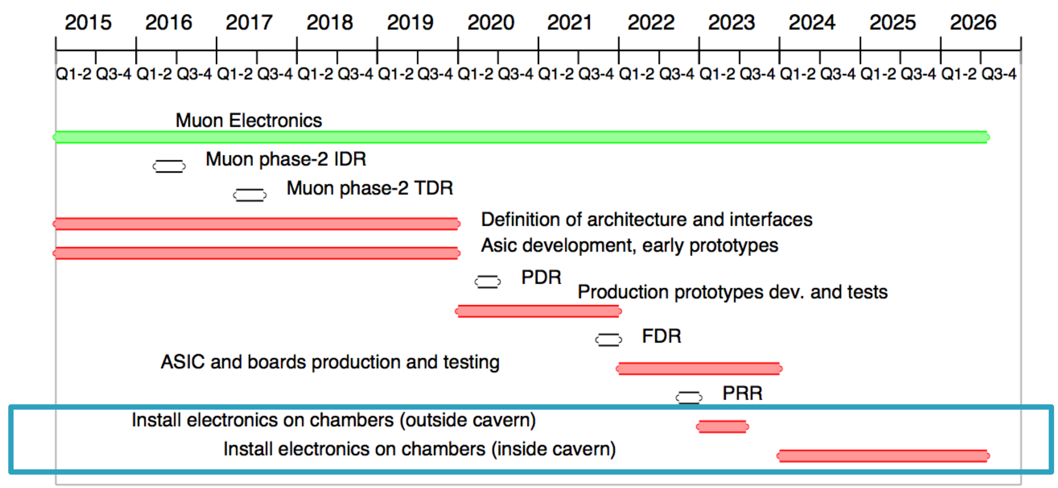
Item	Description
6.6	**Muon**
6.6.1.1	**PCB for Mezzanine - Arizona**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.2	**TDC - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.3	**CSM - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.5	**sMDT - Michigan**
	Chamber Construction
6.6.3.5	**sMDT - MSU**
	Tube Construction
6.6.4.4	**HEB - Illinois**
	Design/Prototype
	Pre-Production
	Production & Testing

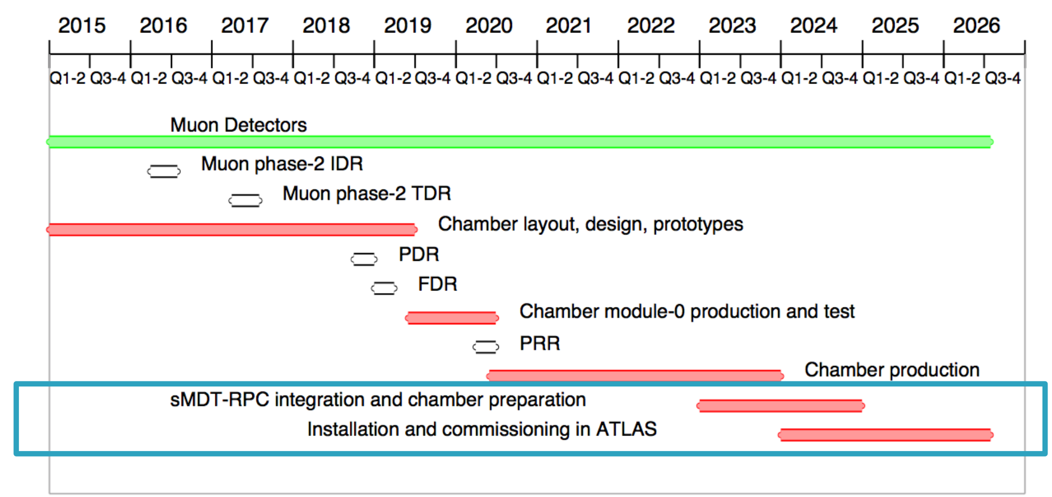




Schedule

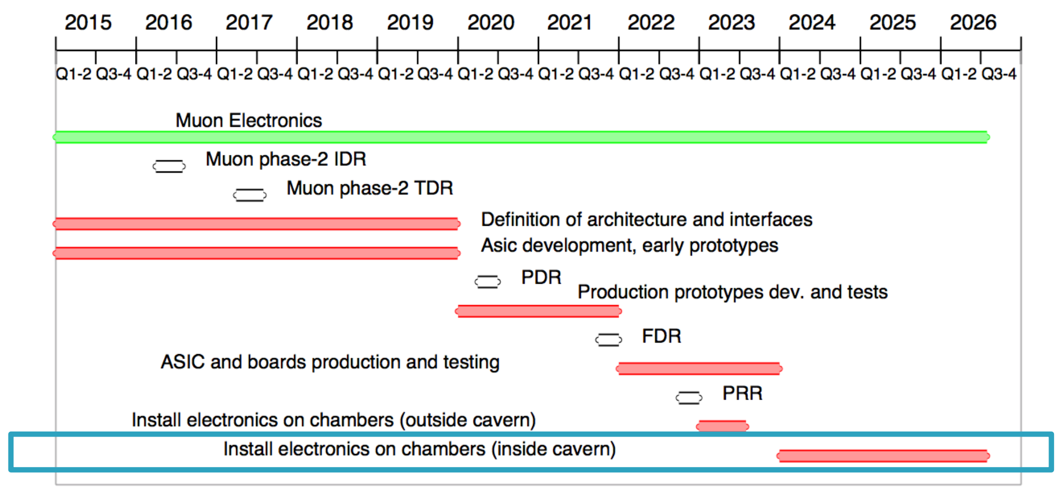
Item	Description
6.6	Muon
6.6.1.1	**PCB for Mezzanine - Arizona**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.2	**TDC - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.3	**CSM - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.5	**sMDT - Michigan**
	Chamber Construction
6.6.3.5	**sMDT - MSU**
	Tube Construction
6.6.4.4	**HEB - Illinois**
	Design/Prototype
	Pre-Production
	Production & Testing

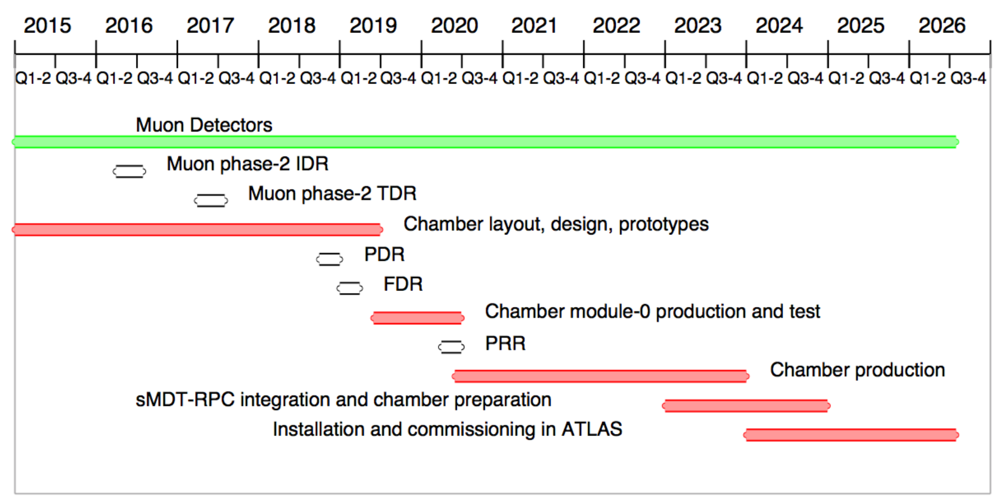




Schedule

Item	Description
6.6	**Muon**
6.6.1.1	**PCB for Mezzanine - Arizona**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.2	**TDC - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.3	**CSM - Michigan**
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.5	**sMDT - Michigan**
	Chamber Construction
6.6.3.5	**sMDT - MSU**
	Tube Construction
6.6.4.4	**HEB - Illinois**
	Design/Prototype
	Pre-Production
	Production & Testing





Schedule

6.6 MUON:START and END and MILESTONES

Item	Description	Start Date	End Date
6.6.1.1	**PCB for Mezzanine - Arizona**	**Q1 FY17**	**Q3 FY23**
Pre-MREFC	*Pre-Construction*	Q1 FY17	Q2 FY20
	Design/Prototype	Q3 FY20	Q4 FY21
MREFC	*Pre-Production*	Q2 FY22	Q1 FY23
	Production and Testing	Q1 FY23	Q3 FY23
	Install electronics on chambers (inside cavern)	Q3 FY24	Q3 FY26
6.6.3.2	**TDC - Michigan**	**Q3 FY16**	**Q1 FY23**
Pre-MREFC	*Pre-Construction*	Q3 FY16	Q2 FY20
	Design/Prototype	Q3 FY20	Q2 FY21
MREFC	*Pre-Production*	Q3 FY21	Q2 FY22
	Production and Testing	Q2 FY22	Q1 FY23
	Install electronics on chambers (outside cavern)	Q3 FY23	Q4 FY23
	Install electronics on chambers (inside cavern)	Q3 FY24	Q3 FY26
6.6.3.3	**CSM - Michigan**	**Q1 FY15**	**Q2 FY23**
Pre-MREFC	*Pre-Construction*	Q1 FY15	Q2 FY20
	Design/Prototype	Q3 FY20	Q3 FY20
MREFC	*Pre-Production*	Q4 FY20	Q4 FY21
	Production and Testing	Q1 FY22	Q2 FY23
	Install electronics on chambers (outside cavern)	Q3 FY23	Q4 FY23
	Install electronics on chambers (inside cavern)	Q3 FY24	Q3 FY26
6.6.3.5	**sMDT - Michigan**	**Q3 FY18**	**Q3 FY22**
Pre-MREFC	*Pre-Construction*	Q3 FY18	Q2 FY20
MREFC	*Chamber Construction*	Q3 FY20	Q3 FY22
	sMDT-RPC integration	Q3 FY23	Q3 FY25
	Installation and Commissioning	Q3 FY23	Q3 FY26
6.6.3.5	**sMDT - MSU**	**Q3 FY18**	**Q2 FY22**
Pre-MREFC	*Pre-Construction*	Q3 FY18	Q2 FY20
MREFC	*Tube Construction*	Q3 FY20	Q2 FY22
	sMDT-RPC integration	Q3 FY23	Q3 FY25
	Installation and Commissioning	Q3 FY23	Q3 FY26
6.6.4.4	**HEB - Illinois**	**Q3 FY17**	**Q2 FY24**
Pre-MREFC	*Pre-Construction*	Q3 FY17	Q2 FY20
	Design/Prototype	Q3 FY20	Q2 FY21
MREFC	*Pre-Production*	Q3 FY21	Q2 FY22
	Production and Testing	Q3 FY22	Q2 FY24
	Installation and Commissioning	Q2 FY25	Q3 FY26

Important Milestones

IDR	**Q3 2016 (June 30th)**	
TDR	**Q3 2017 (June 30th)**	*Likely decision on TDC technology, yet-to-be-decided* *Accessibility of mezzanine cards - yet to be decided*
FDR	**Q4 2022**	

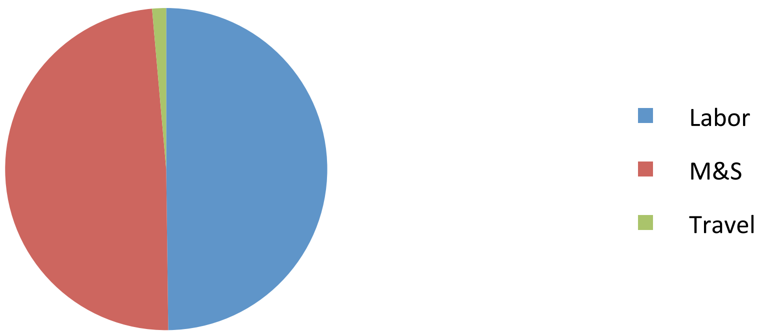
NEED A PLOT and should be compared to budget profile and scoping doc dates

Budget and Effort

Estimates based on the following:

- LABOR: previous experience with similar deliverables and salaries of current employees capable of work - scaled by inflation
- PRODUCTION M&S: similar previous deliverable scaled by inflation, with quotes used for any known new components
- PROTOTYPE M&S: costs scaled from other similar developed prototypes, and quotes from fabrication houses
- TRAVEL: Known travel for specific needs, and some regular travel between collaborating institutions

WBS 6.06 Muon L2 NSF Resource Breakdown

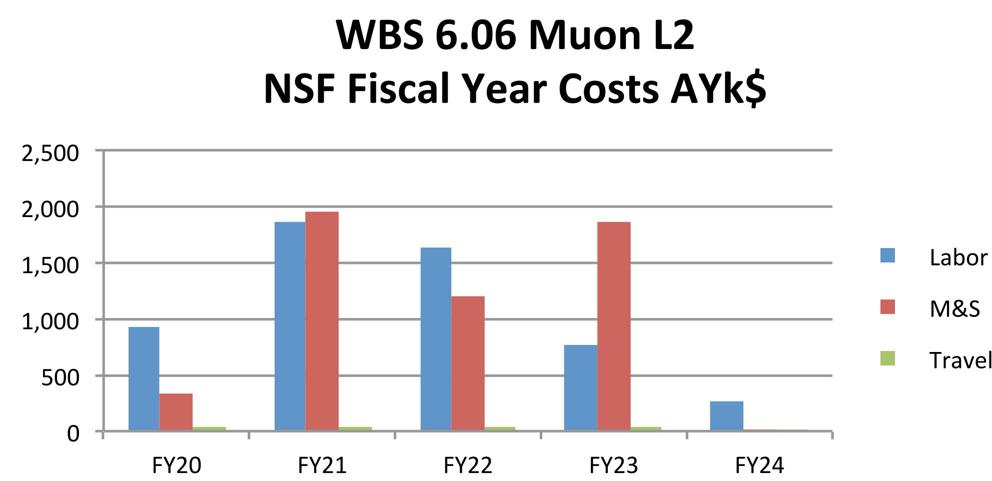


6.06 Muon NSF Total Cost (AYk$)

	FY20	FY21	FY22	FY23	FY24	Grand Total
NSF						
Labor	923	1,874	1,632	764	267	5,460
M&S	339	1,949	1,192	1,868	2	5,350
Travel	28	45	45	27	8	154
NSF Total	**1,291**	**3,868**	**2,869**	**2,659**	**277**	**10,964**

Budget and Effort

- Profile is defined by deliverables needed for sMDT detectors, which are installed earlier. This includes the sMDT's, TDC, and CSM.
- Later required deliverables, the PCB for the MDT's and the HEB, are responsible for the FY23 jump in M&S.
- Engineer Labor is high in early years for design, technician labor ramps to later years for construction

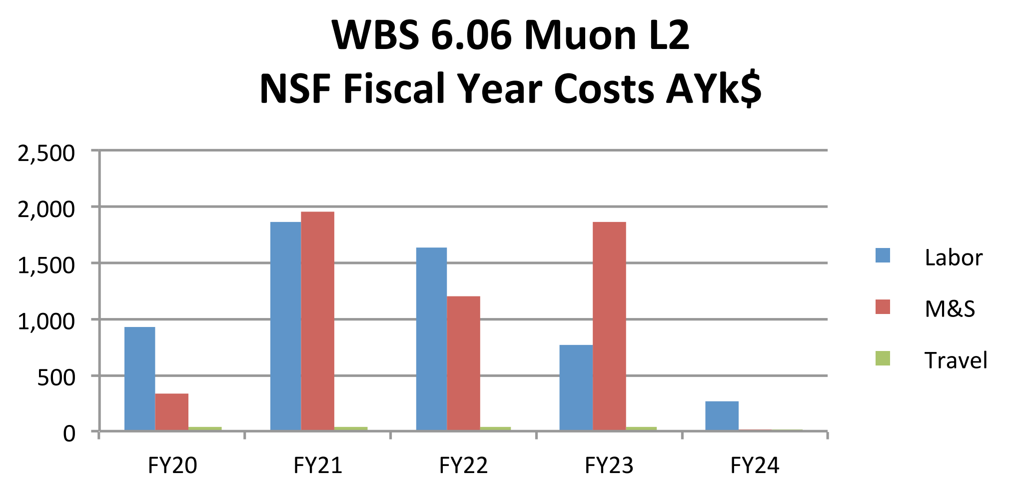


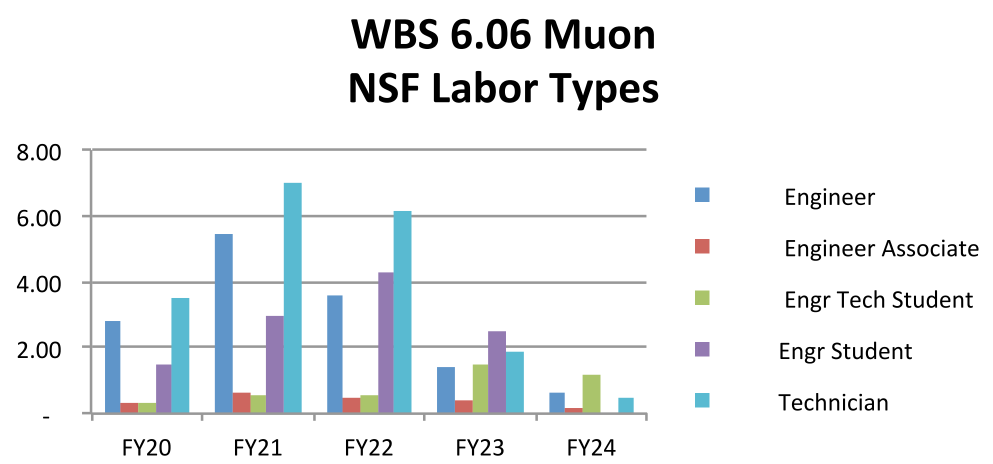
6.06 Muon NSF Total Cost by deliverable (AYk$)

Deliverable/Item	FY20	FY21	FY22	FY23	FY24	Grand Total
6.6.1.1 PCB for Mezzanine	138	261	302	1,253	92	2,046
6.6.3.2 TDC	163	387	919	124	-	1,593
6.6.3.3 CSM	224	1,688	364	156	-	2,432
6.6.3.4 HEB	174	347	348	1,126	185	2,180
6.6.x.5 sMDT	**591**	**1,185**	**936**	-	-	2,713
6.6.3.5 sMDT	321	648	497	-	-	1,466
6.6.5.5 sMDT	270	537	439	-	-	1,246
NSF Grand Total	**1,291**	**3,868**	**2,869**	**2,659**	**277**	**10,964**

Budget and Effort

- Profile is defined by deliverables needed for sMDT detectors, which are installed earlier. This includes the sMDT's, TDC, and CSM.
- Later required deliverables, the PCB for the MDT's and the HEB, are responsible for the FY23 jump in M&S.
- Engineer Labor is high in early years for design, technician labor ramps to later years for construction





6.06 Muon NSF Total FTEs by deliverable

Deliverable/Item	FY20	FY21	FY22	FY23	FY24	Grand Total
6.6.1.1 PCB for Mezzanine	1.02	1.95	1.60	2.14	1.47	8.18
6.6.3.2 TDC	1.50	2.75	2.75	1.50	-	8.50
6.6.3.3 CSM	2.00	4.00	3.90	2.00	-	11.90
6.6.3.4 HEB	1.00	2.00	2.00	2.00	1.00	8.00
6.6.x.5 sMDT	**3.00**	**6.00**	**4.75**	-	-	13.75
6.6.3.5 sMDT	2.00	4.00	3.00	-	-	9.00
6.6.5.5 sMDT	1.00	2.00	1.75	-	-	4.75
NSF Grand Total	**8.52**	**16.70**	**15.00**	**7.64**	**2.47**	**50.33**

Risks

HL-LHC Upgrade Project Risk Registry for L2 Systems
January 4, 2016

WBS	Title	Risk Owner	Risk Evaluation (L/M/H) Cost	Schedule	Scope	Contingency %	Contingency AYK$	Average Risk Score	Identified Risks (See BoEs)
6.6	**Muon**	**Schwarz, Tom**				**35%**	**3,837**	**3.2**	
6.6.x.1	Mezz Card	Johns, K	M	M	M	35%	716	5.0	*The specification, pinout and availability of ASICs. *Final selection of parts might have impact on final costs.
6.6.3.2	TDC	Zhu, J	L	L	L	35%	558	2.0	*Technical difficulties require additional design work and/or prototyping cycle. *Default design will send tube data to CSM without buffering in memory, need to consider an option.
6.6.y.3	CSM	Schwarz, Tom	L	L	L	35%	851	2.0	*Customized board may be required to handle legacy electronics. *If customized board is required and this board requires PCB design this will impact the budget.
6.6.y.4	HEB	Martinez, V	L	L	L	35%	763	2.0	*Availability of technically experience manpower. *Final cost to be determined by size of system and choice of FPGAs, which will depend on the number of required channels
6.6.y.3	sMDT	Zhou, B	L	L	L	35%	949	2.0	*Currency exchange rate fluctuations.

Risks

HL-LHC Upgrade Project Risk Registry for L2 Systems January 4, 2016			Risk Evaluation (L/M/H)						
WBS	Title	Risk Owner	Cost	Schedule	Scope	Contingency %	Contingency AYK$	Average Risk Score	Identified Risks (See BoEs)
6.6	Muon	Schwarz, Tom				35%	[illegible]	3.2	
6.6.x.1	Mezz Card	Johns, K	M	M	M	35%	716	5.0	*The specification, pinout and availability of ASICs. *Final selection of parts might have impact on final costs.
[illegible]	TDC	[illegible]	L	L	L	35%	[illegible]	2.0	*Technical difficulties require additional design work and/or prototyping cycle. *Default design will send tube data to CSM without buffering in memory, need to consider an option.
6.6.y.3	CSM	Schwarz, Tom	L	L	L	35%	851	2.0	*Customized board may be required to handle legacy electronics. *If customized board is required and this board requires PCB design this will impact the budget.
6.6.y.4	HEB	Martinez, V	L	L	L	35%	763	2.0	*Availability of technically experience manpower. *Final cost to be determined by size of system and choice of FPGAs, which will depend on the number of required channels
6.6.y.3	sMDT	Zhou, B	L	L	L	35%	949	2.0	*Currency exchange rate fluctuations.

MITIGATION STRATEGY: Close contact with ASIC developers with mitigate this risk. Decision on ASD/TDC technology happens early — TDR.

Risks

HL-LHC Upgrade Project Risk Registry for L2 Systems
January 4, 2016

WBS	Title	Risk Owner	Risk Evaluation (L/M/H) Cost	Schedule	Scope	Contingency %	Contingency AY K$	Average Risk Score	Identified Risks (See BoEs)
6.6	**Muon**	**Schwarz, Tom**				**35%**	**3,837**	**3.2**	
6.6.x.1	Mezz Card	Johns, K	M	M	M	35%	716	5.0	*The specification, pinout and availability of ASICs. *Final selection of parts might have impact on final costs.
6.6.3.2	TDC	Zhu, J	L	L	L	35%	558	2.0	*Technical difficulties require additional design work and/or prototyping cycle. *Default design will send tube data to CSM without buffering in memory, need to consider an option.
6.6.y.3	CSM	Schwarz, Tom	L	L	L	35%	851	2.0	*Customized board may be required to handle legacy electronics. *If customized board is required and this board requires PCB design this will impact the budget.
6.6.y.4	HEB	Martinez, V	L	L	L	35%	763	2.0	*Availability of technically experience manpower *Final cost to be determined by size of system and choice of FPGAs, which will depend on the number of required channels
6.6.y.3	sMDT	Zhou, B	L	L	L	35%	949	2.0	*Currency exchange rate fluctuations.

<u>MITIGATION STRATEGY</u>: Jr EE has been hired to investigate CSM firmware modifications required if some cards cannot be replaced

Closing Remarks

- From ATLAS muon management point of view, the US CSM and sMDT projects are highest priority
- We are fairly invariant to ATLAS decisions. Projects are high priority and exist in some form in all ATLAS scoping scenarios.
- The TDC and HEB face some international competition. Outcome for the HEB will simply be collaboration. The asic-based TDC could be an option not selected by ATLAS.
- In general, very little risk.
- Institutes working on CSM, HEB, and TDC are already performing R&D towards developing a demonstrator system for the TDR (Due June 30th, 2017).
- Construction phase for muons is FY20 to FY24 - most projects end in FY23

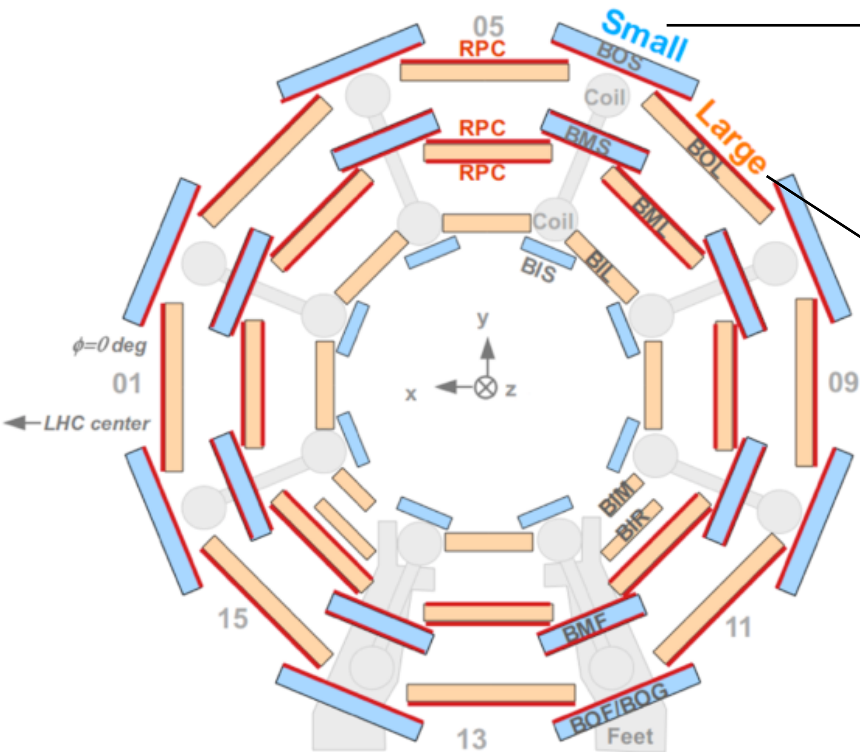
Item	Description
6.6	Muon
6.6.1.1	PCB for Mezzanine - Arizona
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.2	TDC - Michigan
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.3	CSM - Michigan
	Design/Prototype
	Pre-Production
	Production & Testing
6.6.3.5	sMDT - Michigan
	Chamber Construction
6.6.3.5	sMDT - MSU
	Tube Construction
6.6.4.4	HEB - Illinois
	Design/Prototype
	Pre-Production
	Production & Testing

6.06 Muon NSF Total Cost (AYk$)

	FY20	FY21	FY22	FY23	FY24	Grand Total
NSF						
Labor	923	1,874	1,632	764	267	5,460
M&S	339	1,949	1,192	1,868	2	5,350
Travel	28	45	45	27	8	154
NSF Total	**1,291**	**3,868**	**2,869**	**2,659**	**277**	**10,964**

Backup

ATLAS Muon Spectrometer



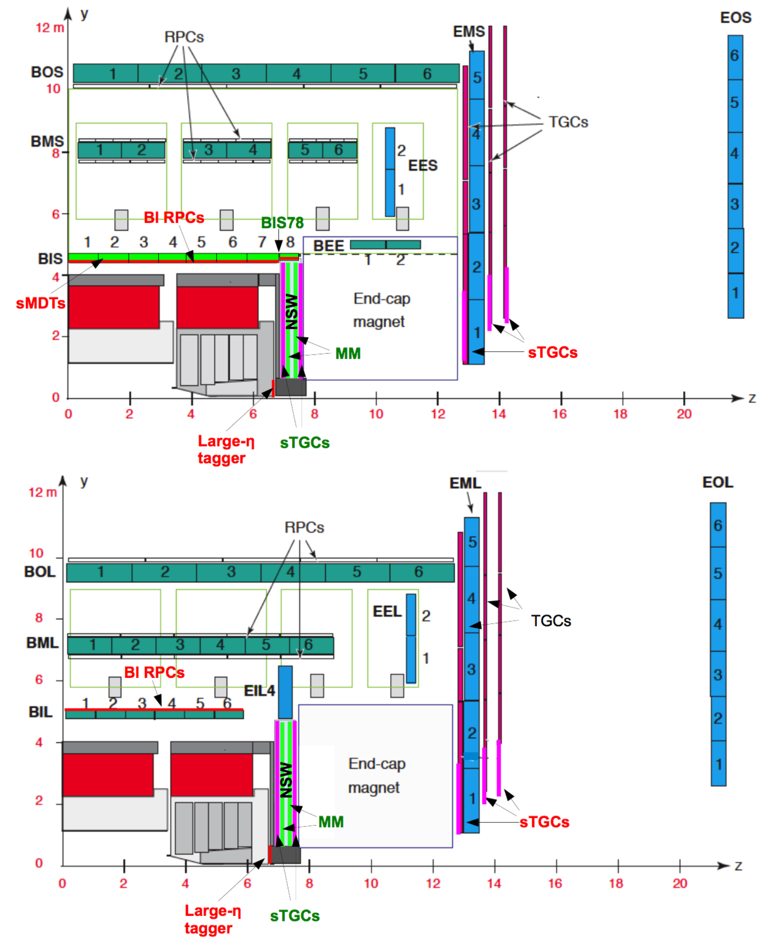


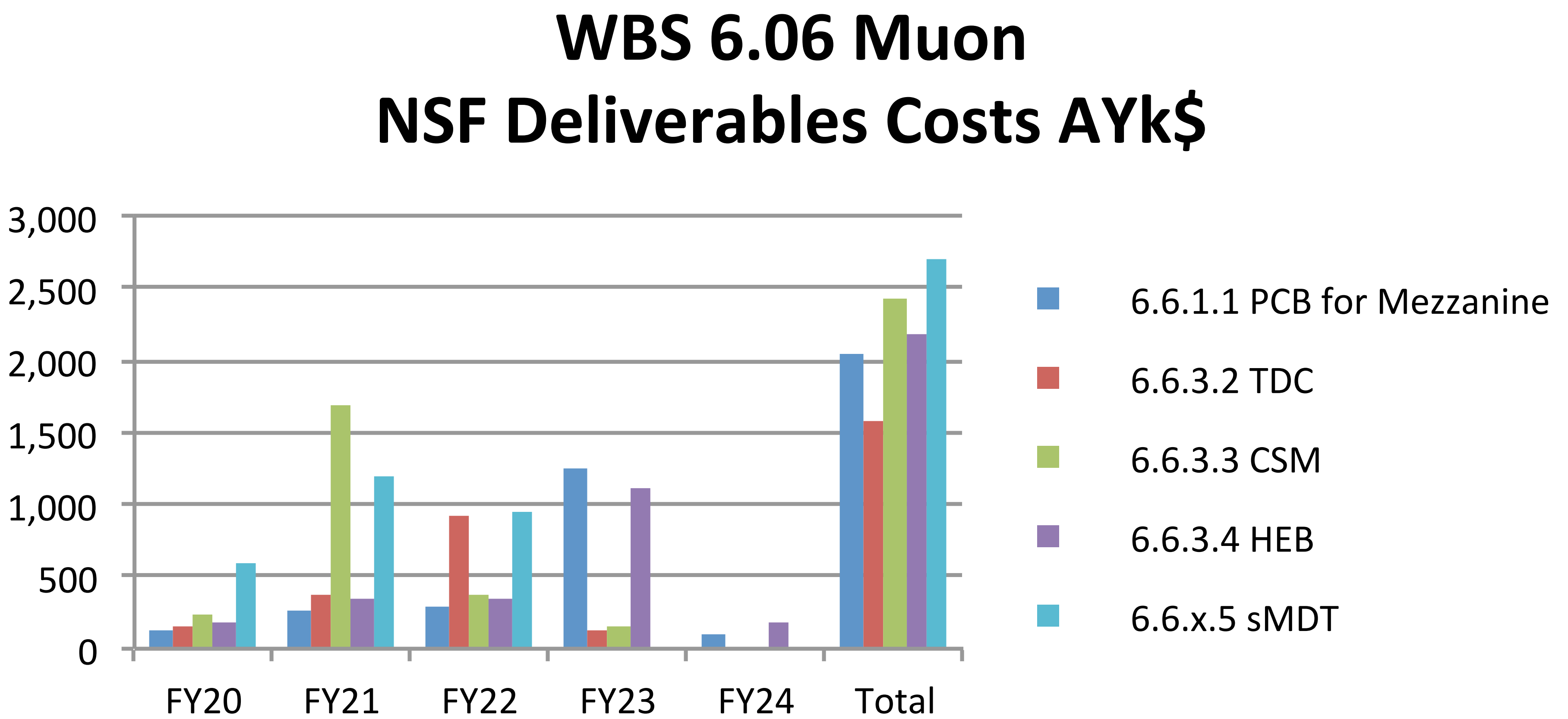
Figure 46. Drawings of the ATLAS Muon Spectrometer with the new chambers proposed for installation in the Phase-II upgrade (red text: BI RPCs, sMDTs, sTGCs, Large-η tagger), those to be installed during LS2 (green text: Micromegas and sTGCs in the new small wheel and RPCs and sMDTs on BIS78), and those that will be kept unchanged from the Run 1 layout (black text). The green (blue) chambers indicated as BMS/BML, BOS/BOL, BEE (EIL, EES/EEL, EMS/EML, EOS/EML) are MDTs. The upper panel shows the R-Z view of one of the azimuthal sectors that contain the barrel toroid coils ("small" sector), the lower panel shows a sector between the barrel toroid coils ("large" sector).

WBS	Item	Reference Total Cost [kCHF]	Middle Differential Cost [kCHF]	Low Differential Cost [kCHF]
5	**Muon system**	**34,084**	**-8,782**	**-12,791**
5.1	**MDT**	**7,692**	**-2,071**	**-3,162**
5.1.1	sMDT detector	2,022	-1,011	-2,022
5.1.2	sMDT installation basket	20	-	-20
5.1.3	Mezzanine cards	4,000	-1,000	-1,000
5.1.4	CSM cards	1,650	-	-
5.2	**RPC**	**7,989**	**-2,318**	**-4,787**
5.2.1	Detectors	3,034	-1,517	-3,034
5.2.2	Installation mock-up	50	-	-50
5.2.3	Installation tooling	100	-	-100
5.2.4	On-detector electronics (DCT)	4,805	-801	-1,603
5.3	**TGC**	**4,436**	**-**	**-**
5.3.1	On-detector electronics (PS)	2,136	-	-
5.3.2	sTGC on BW inner ring	2,300	-	-
5.4	**High η-tagger**	**3,500**	**-3,500**	**-3,500**
5.4.1	Detector	1,100	-1,100	-1,100
5.4.2	FE electronics	1,500	-1,500	-1,500
5.4.3	Services+infrastructure	900	-900	-900
5.5	**Power System**	**10,467**	**-893**	**-1,342**
5.5.1	MDT	2,770	-	-
5.5.2	RPC	4,227	-893	-1,342
5.5.3	TGC	3,470	-	-

Phase II upgrades to the muon spectrometer are required to handle increased rates and fakes associated with HL-LHC luminosities and the new ATLAS wide L0/L1 trigger system

- To cope with high rates
    - The readout of the MDT system must be replaced, as well as the barrel (RPC) and end-cap (TGC) triggering system to cope with high rates at the HL-LHC
    - RPC's will be installed in the inner layer of the barrel to maintain trigger efficiency and increase acceptance, since gas gain in current RPC's will be lowered to meet design limitations (0.3 C/cm2)
- To reduce fakes
    - p_T selectivity of tracks for the trigger will be improved by integrating MDT information into the L1 trigger
    - To reduce fakes at high η ($2 < |\eta| < 2.4$), new sTGC's will replace TGC's in the inner ring of the TGC big wheel
- To extend the muon system lifetime
    - HV and LV power supplies may need to be replaced to ensure operation of the muon spectrometer at the HL-LHC through 2035

Budget and Effort



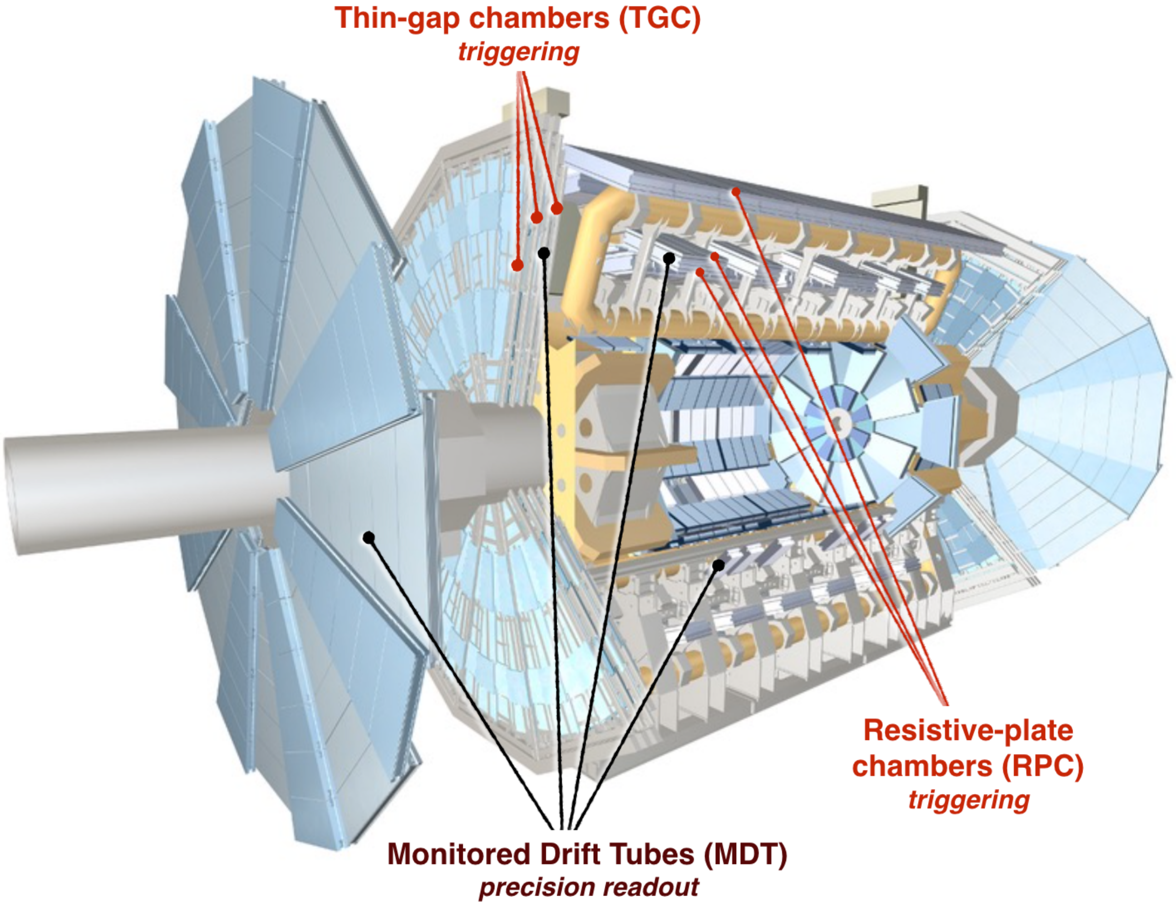
6.06 Muon NSF Level 3 Cost (AYk$)						
	FY20	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
NSF						
6.6.1 Muon_Arizona	138	261	302	1,253	92	2,046
6.6.3 Muon_Michigan	708	2,724	1,780	280	0	5,491
6.6.4 Muon_Illinois	174	347	348	1,126	185	2,180
6.6.5 Muon_MSU	270	537	439	0	0	1,246
NSF Total	**1,291**	**3,868**	**2,869**	**2,659**	**277**	**10,964**

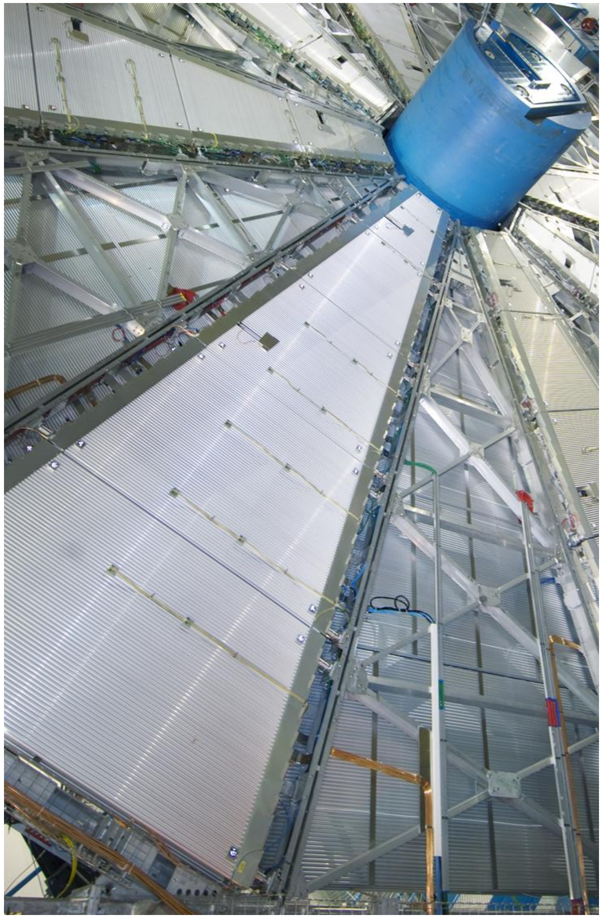
6.06 Muon NSF Total Cost by Phase (AYk$)						
Deliverable/Item/Phase	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
6.6.1 Muon_Arizona	**138**	**261**	**302**	**1,253**	**92**	**2,046**
6.6.1.1 PCB for Mezzanine	**138**	**261**	**302**	**1,253**	**92**	**2,046**
Design	138	261	110	0	0	509
Prototype	0	0	191	65	0	256
Production	0	0	0	1,189	92	1,281
6.6.3 Muon_Michigan	**708**	**2,724**	**1,780**	**280**	**0**	**5,491**
6.6.3.2 TDC	**163**	**387**	**919**	**124**	**0**	**1,593**
Design/Prototype	163	153	0	0	0	316
Pre-Production	0	235	120	0	0	355
Production	0	0	798	124	0	922
6.6.3.3 CSM	**224**	**1,688**	**364**	**156**	**0**	**2,432**
Design/Prototype	105	6	0	0	0	111
Pre-Production	119	435	3	0	0	556
Production	0	1,247	362	156	0	1,765
6.6.3.5 sMDT	**321**	**648**	**497**	**0**	**0**	**1,466**
Tooling Construction	0	0	0	0	0	0
Tube Construction	0	0	0	0	0	0
Chamber Construction	321	648	497	0	0	1,466
6.6.4 Muon_Illinois	**174**	**347**	**348**	**1,126**	**185**	**2,180**
6.6.4.4 HEB	**174**	**347**	**348**	**1,126**	**185**	**2,180**
Design/Prototype	174	168	0	0	0	342
Pre-Production	0	178	173	0	0	352
Production	0	0	175	1,126	185	1,486
6.6.5 Muon_MSU	**270**	**537**	**439**	**0**	**0**	**1,246**
6.6.5.5 sMDT	**270**	**537**	**439**	**0**	**0**	**1,246**
Tooling Construction	0	0	0	0	0	0
Tube Construction	270	537	439	0	0	1,246
Chamber Construction	0	0	0	0	0	0
NSF Grand Total	**1,291**	**3,868**	**2,869**	**2,659**	**277**	**10,964**

6.06 Muon NSF Total FTEs by Phase						
Deliverable/Item/Phase	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**Grand Total**
6.6.1 Muon_Arizona	**1.02**	**1.95**	**1.60**	**2.14**	**1.47**	**8.18**
6.6.1.1 PCB for Mezzanine	**1.02**	**1.95**	**1.60**	**2.14**	**1.47**	**8.18**
Design	1.02	1.95	0.93	-	-	3.90
Prototype	-	-	0.67	0.67	-	1.35
Production	-	-	-	1.47	1.47	2.94
6.6.3 Muon_Michigan	**5.50**	**10.75**	**9.65**	**3.50**	**-**	**29.40**
6.6.3.2 TDC	**1.50**	**2.75**	**2.75**	**1.50**	**-**	**8.50**
Design/Prototype	1.50	1.50	-	-	-	3.00
Pre-Production	-	1.25	1.25	-	-	2.50
Production	-	-	1.50	1.50	-	3.00
6.6.3.3 CSM	**2.00**	**4.00**	**3.90**	**2.00**	**-**	**11.90**
Design/Prototype	0.80	-	-	-	-	0.80
Pre-Production	1.20	4.00	-	-	-	5.20
Production	-	-	3.90	2.00	-	5.90
6.6.3.5 sMDT	**2.00**	**4.00**	**3.00**	**-**	**-**	**9.00**
Tooling Construction	-	-	-	-	-	-
Tube Construction	-	-	-	-	-	-
Chamber Construction	2.00	4.00	3.00	-	-	9.00
6.6.4 Muon_Illinois	**1.00**	**2.00**	**2.00**	**2.00**	**1.00**	**8.00**
6.6.4.4 HEB	**1.00**	**2.00**	**2.00**	**2.00**	**1.00**	**8.00**
Design/Prototype	1.00	1.00	-	-	-	2.00
Pre-Production	-	1.00	1.00	-	-	2.00
Production	-	-	1.00	2.00	1.00	4.00
6.6.5 Muon_MSU	**1.00**	**2.00**	**1.75**	**-**	**-**	**4.75**
6.6.5.5 sMDT	**1.00**	**2.00**	**1.75**	**-**	**-**	**4.75**
Tooling Construction	-	-	-	-	-	-
Tube Construction	1.00	2.00	1.75	-	-	4.75
Chamber Construction	-	-	-	-	-	-
NSF Grand Total	**8.52**	**16.70**	**15.00**	**7.64**	**2.47**	**50.33**

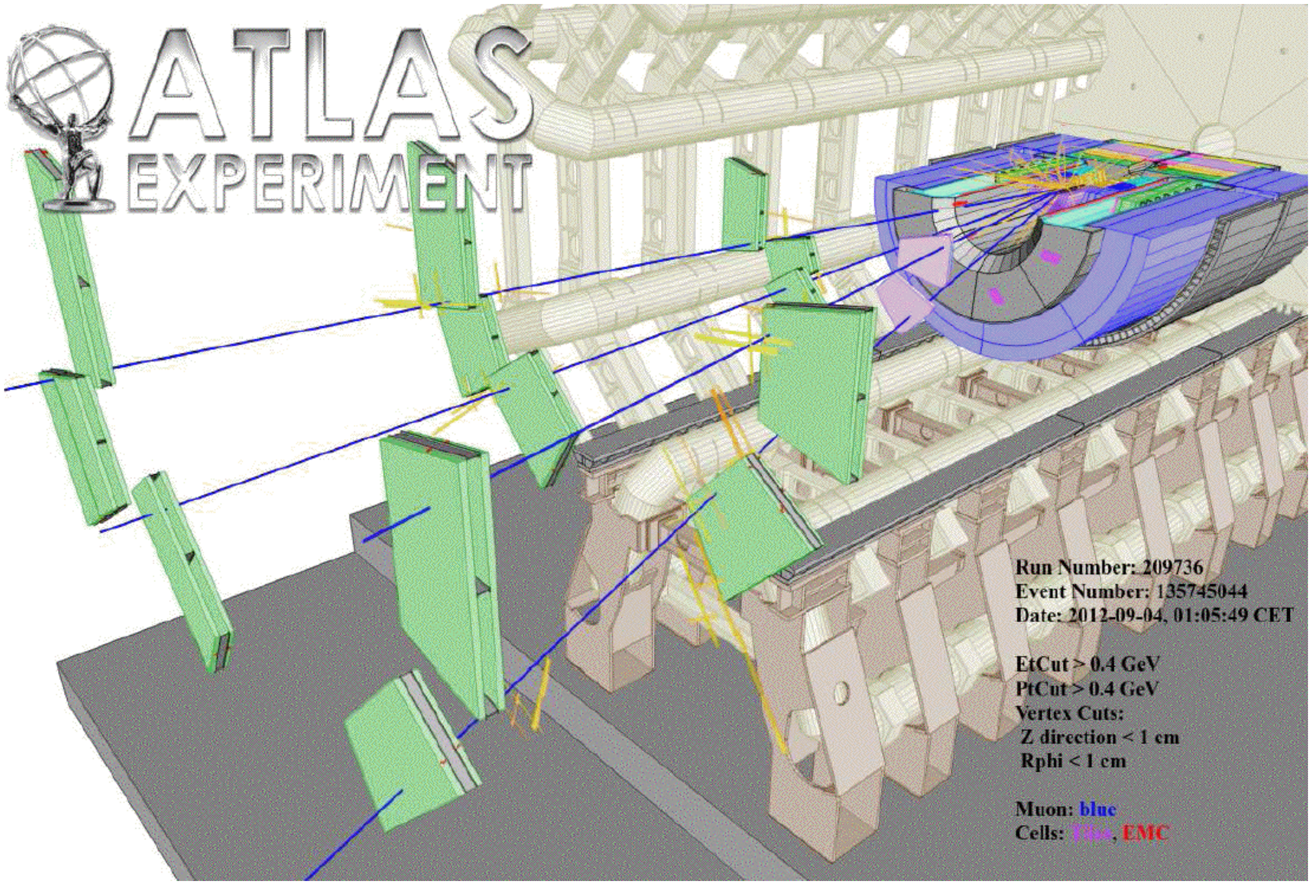
6.06 Muon NSF Total FTEs by Labor Type						
Deliverable/Item	FY20	FY21	FY22	FY23	FY24	Grand Total
6.6.1 Muon_Arizona	**1.02**	**1.95**	**1.60**	**2.14**	**1.47**	**8.18**
6.6.1.1 PCB for Mezzanine	**1.02**	**1.95**	**1.60**	**2.14**	**1.47**	**8.18**
Engineer	0.32	0.72	0.57	0.28	0.11	2.00
Engineer Associate	0.36	0.64	0.46	0.37	0.19	2.02
Engr Tech Student	0.33	0.58	0.58	1.50	1.17	4.17
Engr Student	-	-	-	-	-	-
Technician	-	-	-	-	-	-
6.6.3 Muon_Michigan	**5.50**	**10.75**	**9.65**	**3.50**	**-**	**29.40**
6.6.3.2 TDC	**1.50**	**2.75**	**2.75**	**1.50**	**-**	**8.50**
Engineer	0.50	0.75	0.35	0.10	-	1.70
Engineer Associate	-	-	-	-	-	-
Engr Tech Student	-	-	-	-	-	-
Engr Student	0.50	1.00	1.50	1.00	-	4.00
Technician	0.50	1.00	0.90	0.40	-	2.80
6.6.3.3 CSM	**2.00**	**4.00**	**3.90**	**2.00**	**-**	**11.90**
Engineer	1.00	2.00	0.90	-	-	3.90
Engineer Associate	-	-	-	-	-	-
Engr Tech Student	-	-	-	-	-	-
Engr Student	0.50	1.00	2.00	1.50	-	5.00
Technician	0.50	1.00	1.00	0.50	-	3.00
6.6.3.5 sMDT	**2.00**	**4.00**	**3.00**	**-**	**-**	**9.00**
Engineer	0.50	1.00	0.75	-	-	2.25
Engineer Associate	-	-	-	-	-	-
Engr Tech Student	-	-	-	-	-	-
Engr Student	0.50	1.00	0.75	-	-	2.25
Technician	1.00	2.00	1.50	-	-	4.50
6.6.4 Muon_Illinois	**1.00**	**2.00**	**2.00**	**2.00**	**1.00**	**8.00**
6.6.4.4 HEB	**1.00**	**2.00**	**2.00**	**2.00**	**1.00**	**8.00**
Engineer	0.50	1.00	1.00	1.00	0.50	4.00
Engineer Associate	-	-	-	-	-	-
Engr Tech Student	-	-	-	-	-	-
Engr Student	-	-	-	-	-	-
Technician	0.50	1.00	1.00	1.00	0.50	4.00
6.6.5 Muon_MSU	**1.00**	**2.00**	**1.75**	**-**	**-**	**4.75**
6.6.5.5 sMDT	**1.00**	**2.00**	**1.75**	**-**	**-**	**4.75**
Engineer	-	-	-	-	-	-
Engineer Associate	-	-	-	-	-	-
Engr Tech Student	-	-	-	-	-	-
Engr Student	-	-	-	-	-	-
Technician	1.00	2.00	1.75	-	-	4.75
NSF Grand Total	**8.52**	**16.70**	**15.00**	**7.64**	**2.47**	**50.33**
Engineer	2.82	5.47	3.57	1.38	0.61	13.85
Engineer Associate	0.36	0.64	0.46	0.37	0.19	2.02
Engr Tech Student	0.33	0.58	0.58	1.50	1.17	4.17
Engr Student	1.50	3.00	4.25	2.50	-	11.25
Technician	3.50	7.00	6.15	1.90	0.50	19.05

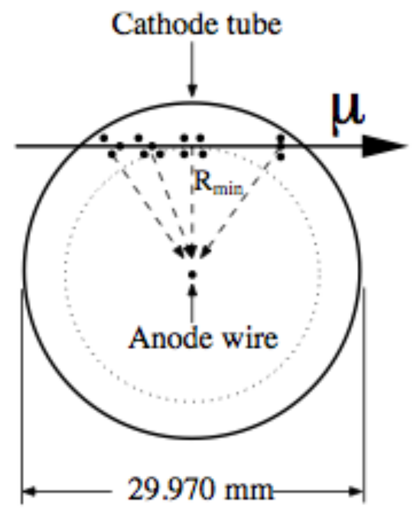
Monitored Drift Tube (MDT) System





Monitored Drift Tube (MDT) System





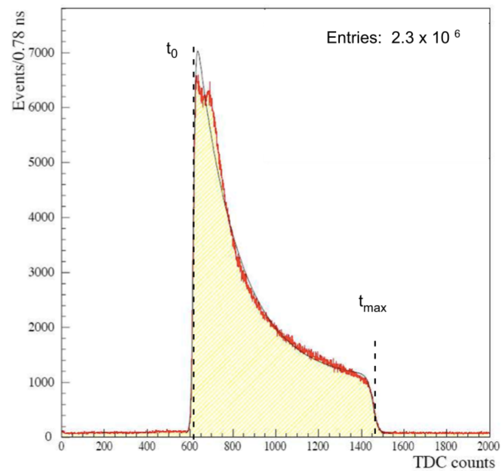


Figure 2: An open chamber of monitored drift tubes (MDT) after assembly.

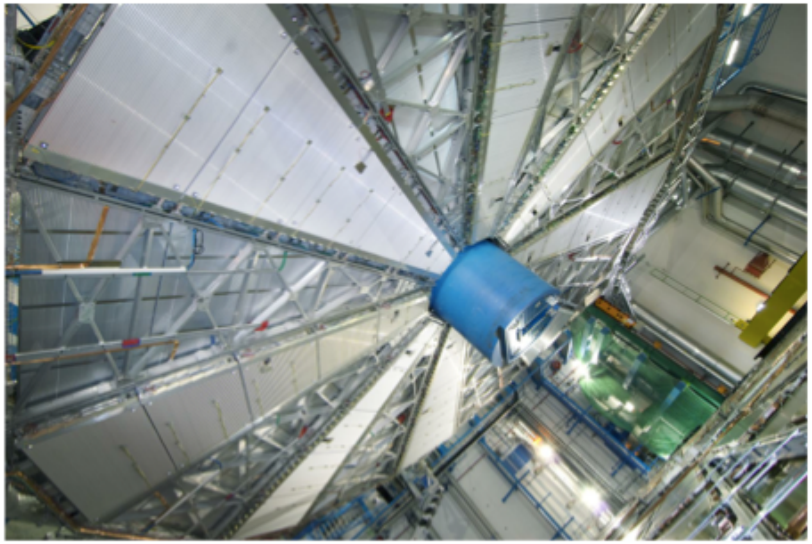
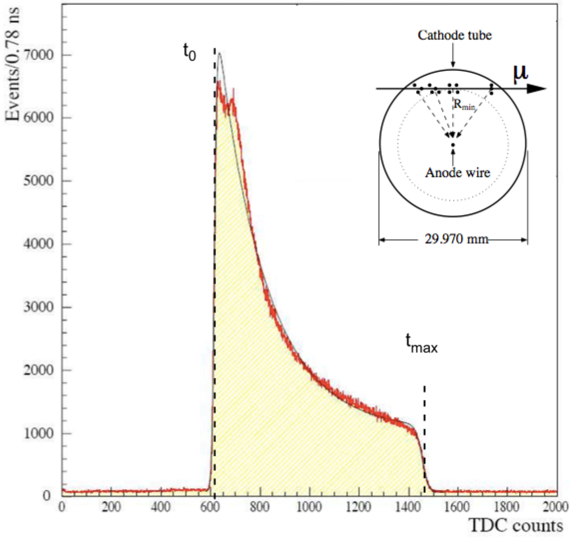
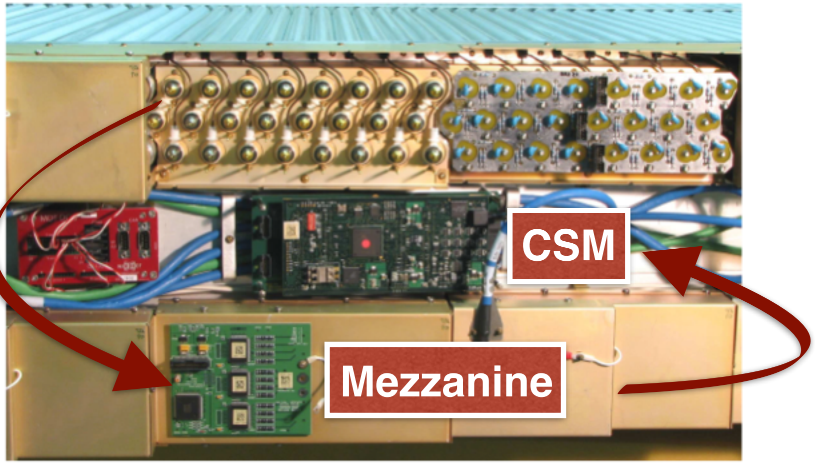


Figure 3: Monitored drift tube chambers in the outer-wheel detector for the forward muon spectrometer of ATLAS.



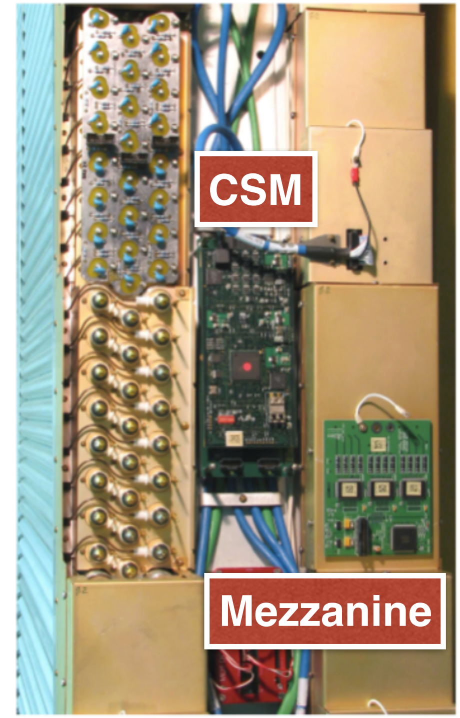


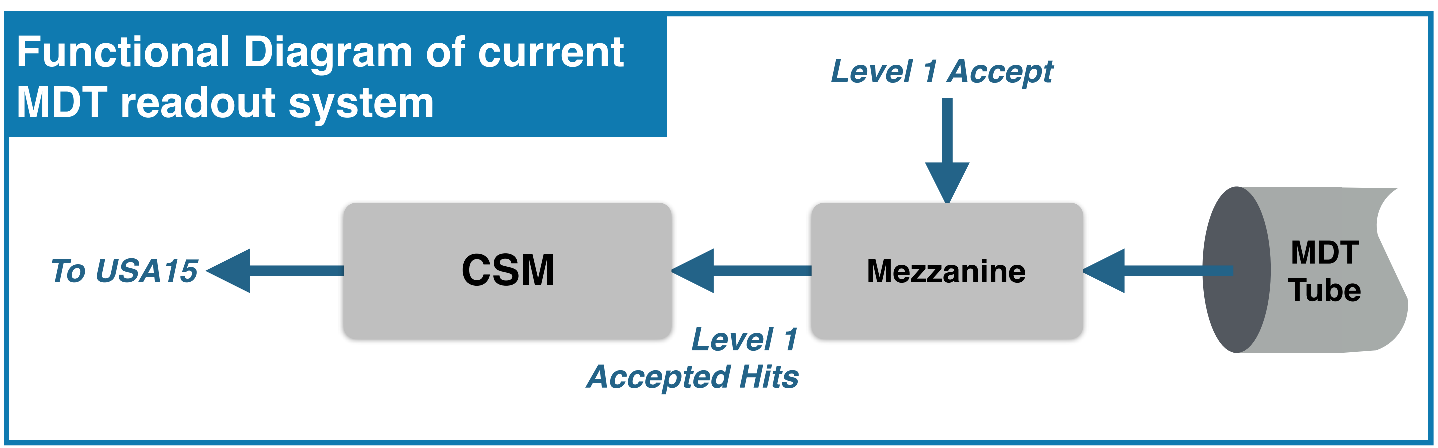
Mezzanine Card

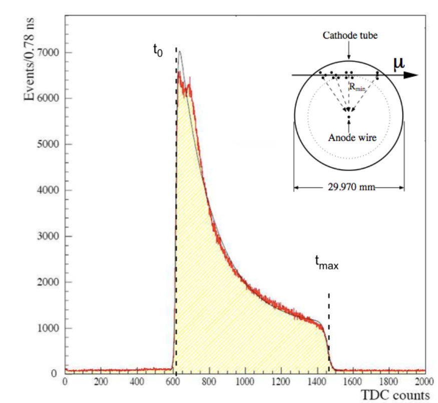
- ➡ Consists of an ADC and TDC which performs sampling, time-stamping, and buffering of candidate Level 1 hits

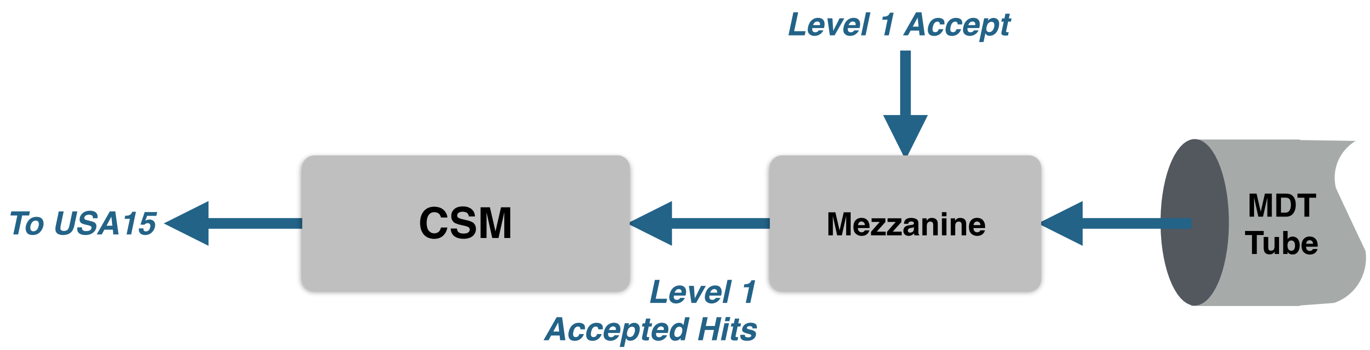
Chamber Service Module (CSM)

- ➡ Routes Level-1 accepted hits to readout at USA15
- ➡ Passes timing information to the TDC for time-stamping
- ➡ Handles control and monitoring

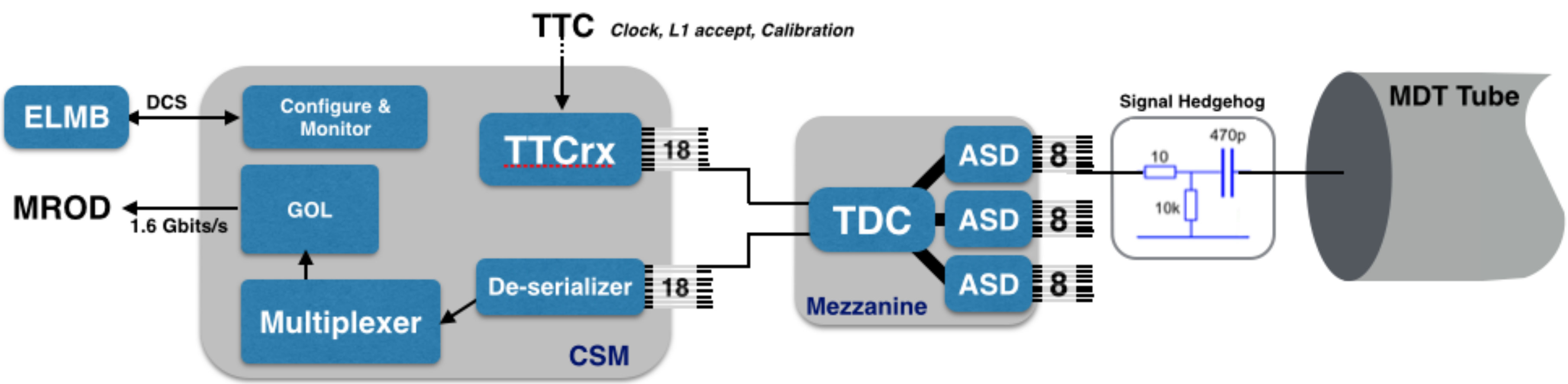


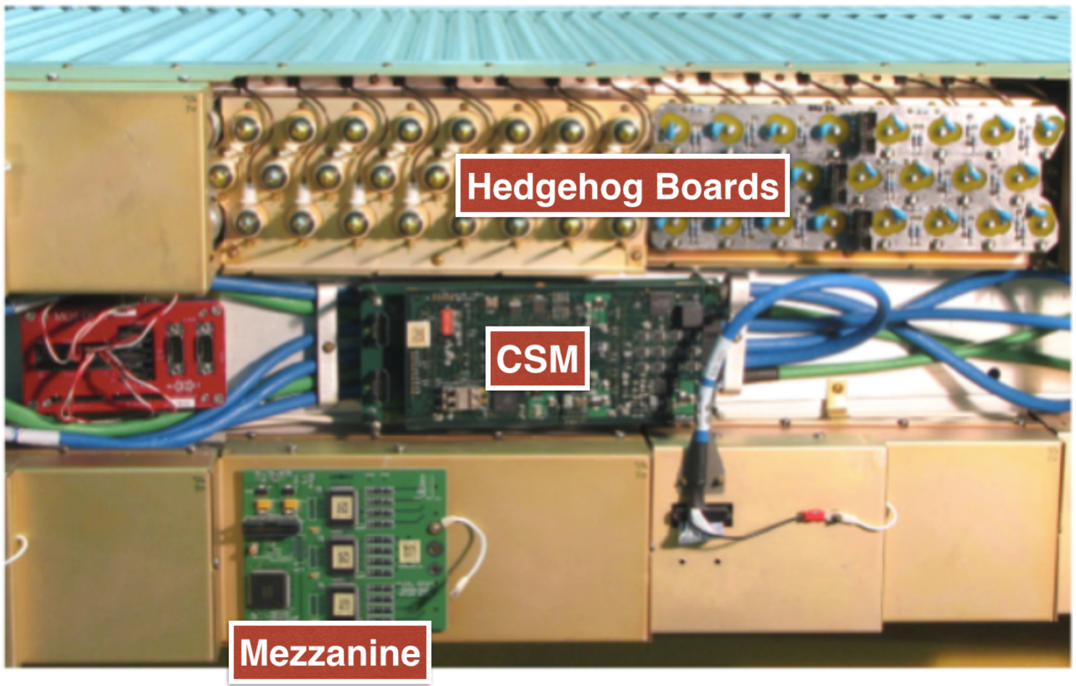


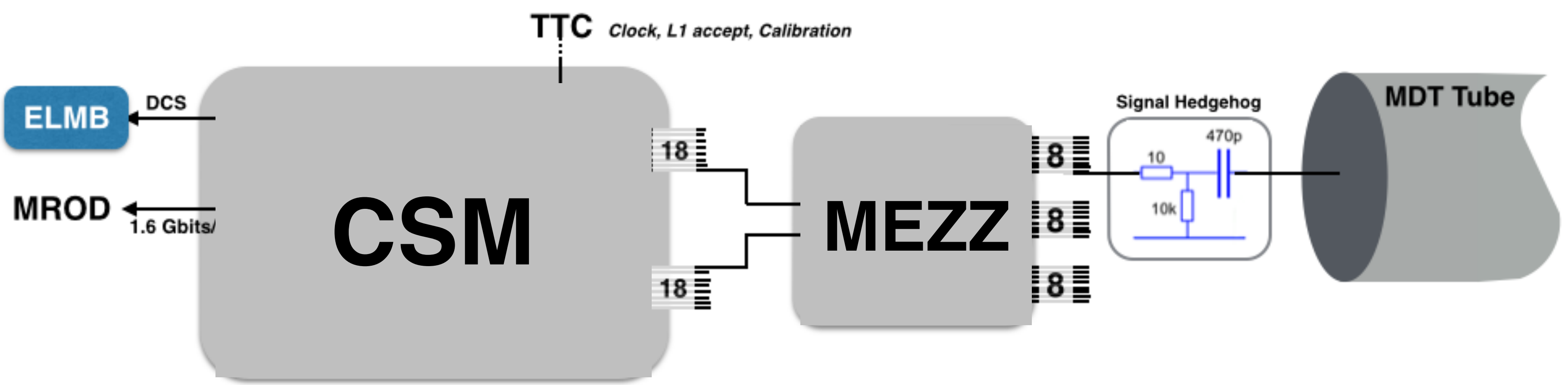




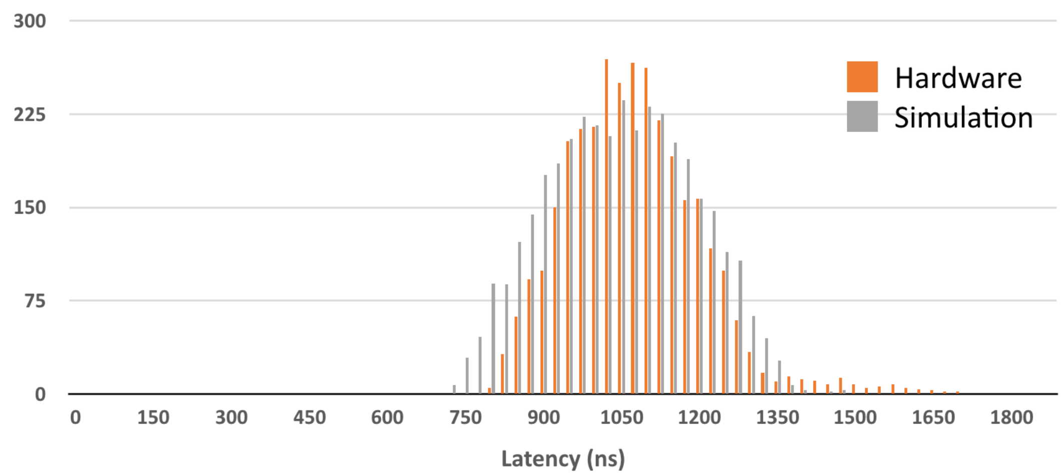
Looking further inside this functional diagram…

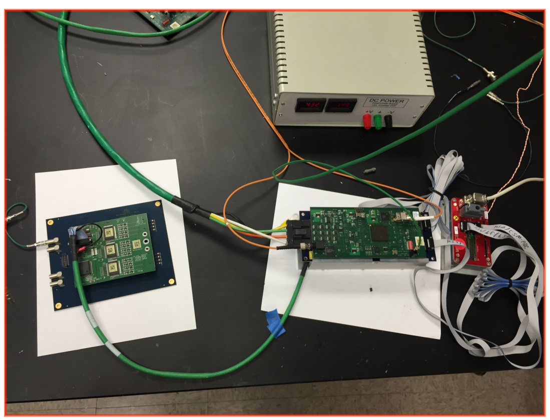


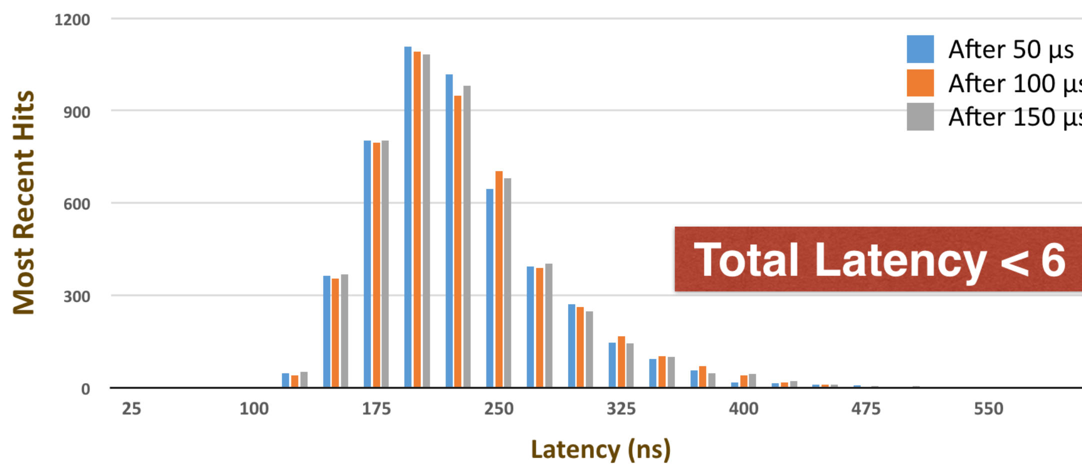

Hedgehog Boards
CSM
Mezzanine


TTC
Clock, L1 accept, Calibration
ELMB
DCS
MROD
1.6 Gbits/
CSM
18
18
MEZZ
8
8
8
Signal Hedgehog
470p
10
10k
MDT Tube

Status of R&D







Total Latency < 6 μs